

UNITED STATES PATENT AND TRADEMARK OFFICE

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BEFORE THE PATENT TRIAL AND APPEAL BOARD

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INNOSCIENCE (ZHUHAI) TECHNOLOGY COMPANY, LTD., AND  
INNOSCIENCE AMERICA, INC.,  
Petitioner,

v.

EFFICIENT POWER CONVERSION CORPORATION,  
Patent Owner

IPR2023-01384  
U.S. Patent No. 10,312,335

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**PETITION FOR *INTER PARTES* REVIEW  
OF U.S. PATENT 10,312,335**

**Declaration of Kelley Hayes Greenhill**

## **I. Introduction**

1. I have prepared this Declaration in connection with the Petition for *Inter Partes* Review of U.S. Patent No. 10,312,335, which I understand will be filed concurrently with this Declaration.

2. I am currently a Senior Manager with the Research & Information Services team at Finnegan, Henderson, Farabow, Garrett & Dunner, LLP, located at 901 New York Avenue, NW, Washington, DC 20001-4413.

3. I am over eighteen years of age, and I am competent to make this Declaration. I make this Declaration based on my own personal knowledge, and my knowledge of library science practices.

4. I earned a Master of Science in Library Science from the Catholic University of America in 1995, and a Bachelor of Arts in Political Science from Duquesne University in 1989. I have work as a librarian for over twenty-five years. I have been employed at Finnegan, Henderson, Farabow, Garrett & Dunner, LLP since 2019. Before that, from 1995– 2015, I was employed in the Library Department of Sterne, Kessler, Goldstein & Fox, PLLC. And from 2015 -2019, I was employed in the Knowledge and Research Service Group (formerly, Information Research Service) at Northrop Grumman Corporation.

5. I am a member of the American Association of Law Libraries.

## **II. Standard Library Practices for Receiving, Cataloging, and Making Materials, Including Serial Publications, Publicly Available (EX1003 and EX1005)**

6. I have knowledge of and experience with standard library practices regarding the receipt, cataloging, shelving, and making materials, including serial publications, available to the public. I have knowledge of and experience with the Machine-Readable Cataloging (MARC) system, an industry-wide standard that libraries use to catalog materials.

7. The MARC system was developed during the 1960s to standardize bibliographic records so they could be read by computers and shared among libraries. By the mid-1970s, MARC had become the international standards for bibliographic data and cataloging. It still used today. Many libraries provide public access to their MARC records via the Internet and/or their electronic cataloging systems at the library.

## **III. Serial Publications**

8. A serial publication, often known as a “journal,” is a resource that is issued in successive parts and has no predetermined conclusion. These successive parts are commonly referred to as “issues,” and each issue is usually chronologically numbered and dated. The presence of enumeration, years of coverage, and/or other chronological information also indicates a serial publication.

9. There are significant differences between cataloging finite resources (books/monographs) and continuing resources (serials). For serials, the catalog record provides information about the serial as a whole, including the first or earliest available issue. It also provides information as to holdings – the volumes and issues, with dates, received by the library and made available to the public. In serials cataloging, there are identifying characteristics unique to serials that are slightly different from monographs (books). The issue date for a print serial publication, for example, generally appears on the cover (front or back), the masthead page, the title page (if any), the table of contents page(s), or on the pages of the individual articles contained in the issue. More information regarding the unique aspects of cataloguing serials can be found at this link:

<https://www.loc.gov/aba/pcc/conser/scctppt/Basic-2014/Basic-Trainee-Manual.pdf>

#### **IV. MARC Records**

10. The MARC record system uses a specific three-digit numeric code (from 001-999) to identify each field in a catalog record. For example, field tag 008 provides the six-digit date the item was catalogued (*Date entered on file*). The first six characters of field tag 008 are always in the “**YYMMDD**” format. Field tag 245 identifies the full title statement for the work; field tag 260 identifies the place of publication, name of publisher, and copyright date of the publication; and



field tag 310 denotes the current frequency of the publication. Finally, field tag 362 identifies the numbering to be used for chronological cataloguing of individual issues of continuing resources (serials). The designations within field 362 determine at what point in time the serial began, which guides how issues are checked in, processed, and added to the library's main collection in an ongoing, consistent manner.

11. Based on standard library practice, when a library receives an item, including a serial, it stamps the item with the library name and often with a date that is within a few days or weeks of receipt. Next, the library will catalog the item within a matter of a few days or weeks of receiving it.

12. Generally, after an item is cataloged, the public may access the item by searching a catalog and either requesting or electronically accessing the item from the library. Standard library practice is to make the item available to the public within a few days or weeks of cataloging it.

## **V. Copyright Office Record**

13. The United States Copyright Office, a part of the Library of Congress, is the official U.S. government body that maintains records of copyright registrations in the United State, including providing public access to an online Copyright Catalog. The records contained in this catalog are publicly accessible

and are routinely used by copyright title researchers who are attempting to clear a chain of title for copyrighted works.

## **VI. IEEE *Xplore***

14. The IEEE *Xplore* digital library is a powerful resource for discovery of scientific and technical content published by the Institute of Electrical and Electronics Engineers (IEEE) and its publishing partners. IEEE *Xplore* provides web access to more than 6 million full-text documents from some of the world's most highly cited publications in electrical engineering, computer science and electronics. Approximately 25,000 new documents are added to IEEE *Xplore* each month. Access to full-text documents in IEEE *Xplore* can be obtained from: institutional subscriptions, exclusive subscription available to IEEE member and IEEE society members, and online purchase of individual documents.

15. The date of publication for journals and standards on IEEE *Xplore* represents the very first instance of dissemination. IEEE *Xplore* previously made distinctions between the online publication date, print publication date, etc. This was simplified to reflect a single publication date of record as defined above.

## **VII. Shenoy 1996 (Exhibit 1009)**

16. As detailed below, I reviewed the University of Wisconsin – Madison Libraries MARC record for its print copies of the *Journal of the Electrochemical Society*, containing R.V. Shenoy and M. Datta, “*Effect of Mask Wall Angles on*

*Shape Evolution during Through-Mask Electrochemical Micromachining.*” The Journal of the Electrochemical Society, Volume 143, Issue 2, pp. 544 -549 (February 1996) ( “*Shenoy*”). I understand that *Shenoy* has been submitted as Exhibit 1009 in this proceeding. **Appendix A** to this declaration is a true and correct copy of the *Shenoy* reference, including the “Web Extra” which was published February 1996.

17. **Appendix B** to this declaration is a true and correct copy of the University of Wisconsin – Madison Libraries public catalog and MARC for its copy of the serial publication *Journal of the Electrochemical Society*, containing *Shenoy*, which was downloaded from:

<https://search.library.wisc.edu/catalog/999478076502121>.

18. The University of Wisconsin – Madison Libraries MARC record for *Shenoy* identifies the fixed data elements of MARC field tag 008 as 741003c19489999nhumr1p 0 a0eng d. This indicates that the serial the *Journal of the Electrochemical Society* was initially catalogued by the University of Wisconsin – Madison Libraries on October 3, 1974. The publication status code “c” appearing in MARC field tag 008 refers to “continuing resource currently published” indicating that this item began publication in 1948 and is a continuing publication received by the library. Based on this MARC record, and the continuous receipt and processing of *Journal of Electrochemical Society* by the

University of Wisconsin – Madison Libraries, *Shenoy* would have been catalogued and made available in print to the public a few days or weeks after February 28, 1996.

19. The University of Wisconsin – Madison Libraries MARC record for *Journal of the Electrochemical Society* containing *Shenoy* includes field tag 245, which denotes the title and statement of responsibility for the work as “Journal of the Electrochemical Society.”

20. In the University of Wisconsin – Madison Libraries MARC catalog record, field tag 260 denotes information relating to the place of publication, name of publisher, and date of publication of *Journal of the Electrochemical Society* as “aNew York, N.Y. :bElectrochemical Society,c1948-. Subfield code “a” refers to the place of publication. Subfield code “b” refers to the name of the publisher. Subfield code “c” refers to date of publication, which for this record is 1948-.

21. In the University of Wisconsin – Madison Libraries MARC catalog record, field tag 362 provides a chronological designation to identify individual issues of a continuing (serial) resource. In this record for *Shenoy*, the sequential designation begins with Vol. 93, no. 1 (Jan. 1948)- with no end date noted.

22. The University of Wisconsin – Madison Libraries public catalog record for *Journal of the Electrochemical Society* sets forth the holdings and onsite location information for members of the public seeking the print issue containing

*Shenoy*. The public catalog record indicates that the *Shenoy* issue is available “by request only S EL278 J82 (51-I-6)” with the holdings noted as v.93:no. 1(1948:Jan) -v. 150:No 12(20023: Dec); v. 151:no. 1 (2204)-v. 152:no. 12(2005) ; Format Journal, Magazine, Newspaper.

23. **Appendix A** to this declaration is a true and accurate copy of the print journal cover, table of contents, and library date stamp for the issue of *Journal of the Electrochemical Society* containing *Shenoy*, which is held by the University of Wisconsin - Madison Libraries. **Appendix A** also includes pages 544 to 549 of this issue, containing the article entitled “*Effect of Mask Wall Angle on Shape Evolution during Through-Mask Electrochemical Micromachining.*” The date stamp inside this issue indicates that *Shenoy* was received by the University of Wisconsin – Madison Libraries February 1996. The print journal cover provides directional information so that members of the interested public can access the print issue containing *Shenoy* in the “Kurt Wendt Library College of Engineering, UW – Madison.”

24. Based on the information in **Appendices A and B**, it is clear that the issue of *Electrochemical Society* containing *Shenoy* was received by University of Wisconsin – Madison Libraries in February 1996. Further, based on standard library practices, *Shenoy*, would have been processed and catalogued within a matter of a few days or weeks of receipt in February 1996.

25. **Appendix C** to this declaration is a true and accurate copy of the U.S Copyright Office record for it copy of the *Journal of the Electrochemical Society*, volume 143, number 2 containing *Shenoy* which was retrieved from [https://cocatalog.loc.gov/cgi-bin/Pwebrecon.cgi?v1=31&ti=26,31&Search%5FArg=journal%20of%20the%20electrochemical%20society&Search%5FCode=TALL&CNT=25&PID=aXK-tN4M\\_61UDN4XRWLECWY&SEQ=20230818155217&SID=2](https://cocatalog.loc.gov/cgi-bin/Pwebrecon.cgi?v1=31&ti=26,31&Search%5FArg=journal%20of%20the%20electrochemical%20society&Search%5FCode=TALL&CNT=25&PID=aXK-tN4M_61UDN4XRWLECWY&SEQ=20230818155217&SID=2). This record indicates a title of *Journal of the Electrochemical Society*, volume 143, number 2 which is the same title and volume, number as found in *Shenoy*. The record denotes the publication date for volume 143, number 2 as February 22, 1996.

26. Based on the information in this **Appendix C** the issue of *the Journal of the Electrochemical Society*, containing *Shenoy* would have been publicly available within a few days or weeks of February 22, 1996.

#### **VIII. Xu 2007 (Exhibit 1014)**

27. As detailed below, I reviewed the British Library MARC record for its print copies of the *IEEE Electron Device Letters*, containing Chuan Xu, Jinyan Wang, Hongwei Chen, Fujun Xu, Zhihua Dong, Yilong Hao, and Cheng P. Wen, “*The Leakage Current of the Schottky Contact on the Mesa Edge of AlGaIn/GaN Heterostructure.*” *IEEE Electron Device Letters*, Volume 28, Issue 11, pp. 942 - 944 (November 2007) (“*Xu*”). I understand that *Xu* has been submitted as Exhibit

1014 in this proceeding. **Appendix D** to this declaration is a true and correct copy of the *Hu* reference.

28. **Appendices E** to this declaration is a true and correct copy of the British Library MARC for its copy of the serial publication *IEEE Electron Device Letter*, containing *Xu*, which was downloaded from:  
<http://explore.bl.uk/BLVU1:LSCOP-ALL:BLL01009844648> and  
[http://primocat.bl.uk/F/?func=direct&local\\_base=PRIMO&doc\\_number=009844648&format=001&con\\_lng=eng](http://primocat.bl.uk/F/?func=direct&local_base=PRIMO&doc_number=009844648&format=001&con_lng=eng).

29. The British Library MARC record for *Xu* identifies the fixed data elements of MARC field tag 008 as 800820c19809999xxumr p 0 a0eng . This indicates that the serial the *IEEE Electron Device Letters* was initially catalogued by the British Library on August 20, 1980. The publication status code “c” appearing in MARC field tag 008 refers to “continuing resource currently published” indicating that this item began publication in 1980 and is a continuing publication received by the library. Based on this MARC record, and the continuous receipt and processing of *IEEE Electron Device Letters* by the British Library, *Xu* would have been catalogued and made available in print to the public a few days or weeks after receipt.

30. The British Library MARC record for *IEEE Electron Device Letters* containing *Xu* includes field tag 245, which denotes the title and statement of responsibility for the work as “IEEE Electron Device Letters.”

31. In the British Library MARC catalog record, field tag 260 denotes information relating to the place of publication, name of publisher, and date of publication of *IEEE Electron Device Letters* as “a New York : |b IEEE , |c 1980-”. Subfield code “a” refers to the place of publication. Subfield code “b” refers to the name of the publisher. Subfield code “c” refers to the copyright date.

32. In the British Library MARC catalog record, field tag 3620 provides a chronological designation to identify individual issues of a continuing (serial) resource. In this record for *Xu*, the sequential designation begins with Vol. EDL -1, no. 1 (Jan. 1980)- with no end date noted.

33. **Appendix F** to this declaration is a true and correct copy British Library public catalog record for *IEEE Electron Device Letters* sets forth the holdings and onsite location information for members of the public seeking the print issue containing *Xu*. The public catalog record indicates that the *Xu* issue is available in Document Supply 4362.922800 Vol. 1, no 1 (1980)-v. 34, no. 1 (2013)\*\*\* UKRR Retained Title\*\*\* Stock incomplete; Science Technology and Business (P) RK 00-E(87) Vol. EDL-1 (180)-v/ 21; (2000)\*\*\*UKRR Retained Title\*\*\*Deficient: vol.EDL-3, no. 11, 1982: vo. EDL-9, no. 12, 1989.



34. **Appendix D** to this declaration is a true and accurate copy of the print journal cover, table of contents, and library date stamp for the issue of *IEEE Electron Device Letters* containing *Xu*, which is held by the British Library. **Appendix D** also includes pages 942 to 944 of this issue, containing the article entitled “*The Leakage Current of the Schottky Contact on Mesa Edge of AlGaIn/GaN Heterostructure.*” The date stamp on the cover this issue indicates that *Xu* was received by the British Library in November 2007.

35. Based on the information in **Appendices D, E and F**, it is clear that the issue of *IEEE Electron Device Letters* containing *Xu* was received by British Library in November 2007. Further, based on standard library practices, *Xu*, would have been processed and catalogued within a matter of a few days or weeks of receipt in November 2007.

36. **Appendix G** to this declaration is a true and accurate copy of the IEEE *Xplore* record for *Xu*. This record indicates the article entitled “*The Leakage Current of the Schottky Contact on Mesa Edge of AlGaIn/GaN Heterostructure*” was published in *IEEE Electron Device Letters* (Volume: 28, Issue: 11, November 2007), Page(s): 942 – 944. Further, this record indicates a publication date of October 29, 2007.

37. Based on the information in **Appendix G**, it is clear that the issue of *IEEE Electron Device Letters* containing *Xu* was published by IEEE *Xplore* on

October 29, 2007. *Xu* would have been disseminated within a matter of a few days or weeks of receipt of October 29, 2007.

**IX. *Hu* 2008 (Exhibit 1018)**

38. As detailed below, I reviewed the University of Missouri – Kansas City, Linda Hall Library MARC record for its print copies of the *Electronics Letters*, containing X. Hu, G. Simin, J. Yang, M. Asif Khan, R. Gaska and M.S. Shur, “*Enhancement mode AlGaIn/GaN HFET with Selectively Grown PN Junction Gate.*” *Electronics Letters*, Volume 36, Issue 8, pp. 753 -754 (April 2000) (“*Hu*”). I understand that *Hu* has been submitted as Exhibit 1018 in this proceeding. **Appendix H** to this declaration is a true and correct copy of the *Hu* reference.

39. **Appendix I** to this declaration is a true and correct copy of the Linda Hall Library public catalog and MARC for its copy of the serial publication *Electronics Letters*, containing *Hu*, which was downloaded from:

[https://catalog.lindahall.org/permalink/01LINDAHALL\\_INST/19lda7s/alma995137993405961](https://catalog.lindahall.org/permalink/01LINDAHALL_INST/19lda7s/alma995137993405961).

40. The Linda Hall Library MARC record for *Hu* identifies the fixed data elements of MARC field tag 008 as 750824c19659999enken p 0 a0eng d. This indicates that the serial the *Electronics Letters* was initially catalogued by the Linda Hall Library on August 24, 1975. The publication status code “c” appearing

in MARC field tag 008 refers to “continuing resource currently published” indicating that this item began publication in 1965 and is a continuing publication received by the library. Based on this MARC record, and the continuous receipt and processing of *Electronics Letters* by the Linda Hall Library, *Hu* would have been catalogued and made available in print to the public a few days or weeks after receipt.

41. The Linda Hall Library MARC record for *Electronics Letters* containing *Hu* includes field tag 245, which denotes the title and statement of responsibility for the work as “Electronics Letters.”

42. In the Linda Hall Library MARC catalog record, field tag 260 denotes information relating to the place of publication, name of publisher, and date of publication of *Electronics Letters* as “aStevenage, UK :bInstitution of Electrical Engineers. Subfield code “a” refers to the place of publication. Subfield code “b” refers to the name of the publisher.

43. In the Linda Hall Library MARC catalog record, field tag 362 provides a chronological designation to identify individual issues of a continuing (serial) resource. In this record for *Hu*, the sequential designation begins with Vol. 1 (Mar. 1965)- with no end date noted.

44. **Appendix J** to this declaration is a true and correct copy The Linda Hall Library public catalog record for *Electronics Letters* sets forth the holdings

and onsite location information for members of the public seeking the print issue containing *Hu*. The public catalog record indicates that the *Hu* issue is “available” in the “closed stacks” with the holdings noted as v.1 (1965) – v.34 (1998); v.35: np.1-3, 6-25 (1999); v.36 (2000)-v.46 (2010); v.47:no.1(2011: Jan.6)-v.47:no.10(2011:May 12). v.47:no.13(2011:Jun.23)-v.49:no.25 (2013:Dec.5)-.

45. **Appendix H** to this declaration is a true and accurate copy of the print journal cover, table of contents, and library date stamp for the issue of *Electronics Letters* containing *Hu*, which is held by the Linda Hall Library. **Appendix H** also includes pages 753 to 754 of this issue, containing the article entitled “*Enhancement Mode AlGaIn/GaN HFET with Selectively Grown PN Junction Gate.*” The date stamp inside this issue indicates that *Hu* was received by the Linda Hall Library on May 2, 2000. The print journal cover provides directional information so that members of the interested public can access the print issue containing *Hu* in the “Linda Hall Library.”

46. Based on the information in **Appendices H, I and J**, it is clear that the issue of *Electronics Letters* containing *Hu* was received by Linda Hall Library on May 2, 2000. Further, based on standard library practices, *Hu*, would have been processed and catalogued within a matter of a few days or weeks of receipt of May 2, 2000.

## **X. Conclusion**

47. In signing this Declaration, I understand it will be filed as evidence in a contested case before the Patent Trial and Appeal Board of the United States Patent and Trademark Office. I understand I may be subject to cross-examination in this case and that cross-examination will take place within the United States. If cross-examination is required of me, I will appear for cross-examination within the United States during the time allotted for cross-examination.

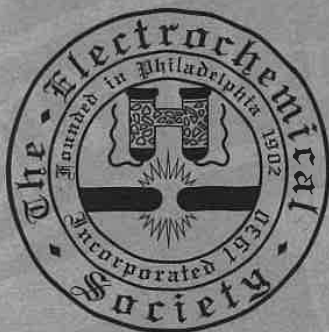
48. I declare that all statements made herein of my knowledge are true, that all statements made on information and belief are believed to be true, and that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code.

Executed on September 6, 2023, in Washington, DC.

*Kelley Hayes Greenhill*  
\_\_\_\_\_  
Kelley Hayes Greenhill

# APPENDIX A

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EL278  
J82



# Journal of The Electrochemical Society

LIBRARY  
COLLEGE OF ENGINEERING

1996

LIBRARY

**A Journal for Solid-State and  
Electrochemical Science and Technology**

**Volume 143, Number 2  
February 1996**

*JESOAN 143 (2) L21-L48, 391-758, 15C-18C*

# Table of Contents

## Electrochemical Society Letters

<b>In Situ FTIR-Diffuse Reflection Spectroscopy of the Anode Surface in a Direct Methanol/Oxygen Fuel Cell</b> <i>Q. Fan, C. Pu, K. L. Ley, E. S. Smotkin</i> .....	L21
<b>Promoting Effect of Sodium Dodecyl Sulfate on the Redox Reaction of Hemoglobin</b> <i>G.-X. Li, H.-Q. Fang, X.-M. Liao, H.-R. Shi, H.-Y. Chen</i> .....	L24
<b>Effects of the Organic Solvent on the Electrochemical Lithium Intercalation Behavior of Graphite Electrode</b> <i>M. Morita, T. Ichimura, M. Ishikawa, Y. Matsuda</i> .....	L26
<b>A New Type of a Rocking-Chair Battery Family Based on a Graphite Anode and a Polymer Cathode</b> <i>S. Panero, E. Spila, B. Scrosati</i> .....	L29
<b>The Role of Microcracking in ZrCrNi Hydride Electrodes</b> <i>M. McCormack, M. E. Badding, B. Vyas, S. M. Zaburak, D. W. Murphy</i> .....	L31
<b>Mixed Potential Type NO<sub>x</sub> Sensor Based on Stabilized Zirconia and Oxide Electrode</b> <i>N. Miura, G. Lu, N. Yamazoe, H. Kurosawa, M. Hasei</i> .....	L33
<b>Selective CO Detection by Using Indium Oxide-Based Semiconductor Gas Sensor</b> <i>H. Yamaura, J. Tamaki, K. Moriya, N. Miura, N. Yamazoe</i> .....	L36
<b>Control of Selective Tungsten Chemical Vapor Deposition by Monolayer Nitridation of Silicon Surface</b> <i>S. Takami, T. Saito, M. Fujii, Y. Egashira, H. Komiyama</i> .....	L38
<b>Bevel Etching of Tin-Doped Indium Oxide</b> <i>J. E. A. M. van den Meerakker, J. W. M. Jacobs</i> .....	L40
<b>Fabrication of a Porous Silicon Diode Possessing Distinct Red and Orange Electroluminescent Regions</b> <i>L. Zhang, J. L. Colfer, Y. G. Rho, R. F. Pinizzotto</i> .....	L42
<b>A Novel Electrochemical Method for Measuring Salt Diffusion Coefficients and Ion Transference Numbers</b> <i>J. Xu, G. C. Farrington</i> .....	L44

## Electrochemical Science and Technology

<b>Reactivity of Lithium Intercalated into Petroleum Coke with Carbonate Electrolytes</b> <i>M. Jean, A. Tranchant, R. Messina</i> .....	391
<b>Nanocrystalline TiO<sub>2</sub> (Anatase) Electrodes: Surface Morphology, Adsorption, and Electrochemical Properties</b> <i>L. Kavan, M. Grätzel, J. Rathbousky, A. Zukal</i> .....	394
<b>Voltammetry and Conductivity of a Polyether-Pyridinium Room Temperature Molten Salt Electrolyte and of Its Polymer Electrolyte Solutions in Polydimethylsiloxane</b> <i>R. Pyati, R. W. Murray</i> .....	401
<b>Sodium/Phosphorus-Sulfur Cells.</b>	
<b>I. Cell Performance</b> <i>P. L. Ridgway, F. R. McLarnon, E. J. Cairns</i> .....	406
<b>Sodium/Phosphorus-Sulfur Cells.</b>	
<b>II. Phase Equilibria</b> <i>P. L. Ridgway, F. R. McLarnon, E. J. Cairns</i> .....	412
<b>The Effect of Mechanical Processing Procedures on the Decomposition Rate of Silver Oxide Cathode Material</b> <i>K. Takeda</i> .....	418
<b>The Reaction of Clean Li Surfaces with Small Molecules in Ultrahigh Vacuum.</b>	
<b>I. Dioxygen</b> <i>K. Wang, P. N. Ross, Jr., F. Kong, F. McLarnon</i> .....	422



The Journal of The  
Electrochemical Society

February 1996 • Vol. 143, No. 2

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The Electrochemical Society is an educational, nonprofit 501(c)(3) organization with more than 7000 scientists and engineers in over 65 countries world-wide who hold individual membership. Founded in 1902, the Society has a long tradition in advancing the theory and practice of electrochemical and solid state science by dissemination of information through its publications and international meetings.

**The Journal of The Electrochemical Society** (USPS 284-140) (ISSN 0013-4651) is published monthly by The Electrochemical Society, Inc., 10 South Main Street, Pennington, NJ 08534-2896, USA, at Cummings Printing Co., 4 Peters Brook Drive, PO Box 16495, Hooksett, NH 03106-6495, USA. Subscription to members as part of membership service. Annual Membership dues: \$90 for Active Members and \$10 for Student Members. Subscription to nonmembers \$425 plus \$25 for postage outside U.S. Single copies \$15 for members and \$35 for nonmembers.

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## Publication Information

**Address:** The mailing address for the Executive Offices, Editorial Department and the Circulation Department of The Electrochemical Society is: 10 South Main Street, Pennington, New Jersey, 08534-2896, USA. The telephone number is (609) 737-1902. The Fax number is (609) 737-2743, and e-mail may be sent to: [ecs@electrochem.org](mailto:ecs@electrochem.org).

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<b>Studies of Electrochemical Properties of <math>\text{Ti}_{0.35}\text{Zr}_{0.65}\text{Ni}_x\text{V}_{2-x-y}\text{Mn}_y</math> Alloys with C14 Laves Phase for Nickel/Metal Hydride Batteries</b> <i>H. W. Yang, Y. Y. Wang, C. C. Wan</i> .....	429
<b>Application of Porous Electrode Theory on Metal Hydride Electrodes in Alkaline Solution</b> <i>G. Zheng, B. N. Popov, R. E. White</i> .....	435
<b>Corrosion of Tin Oxide at Anodic Potentials</b> <i>H. Cachet, M. Froment, F. Zenia</i> .....	442
<b>The Detection and Analysis of Electrochemical Damage in Bismaleimide/Graphite Fiber Composites</b> <i>S. R. Taylor, F. D. Wall, G. L. Caben, Jr.</i> .....	449
<b>Anodic Behavior of Copper in Iodide Solutions. Comparison with Chloride and Effect of Benzotriazole-Type Inhibitors</b> <i>D. Tromans, J. C. Silva</i> .....	458
<b>Kinetics of Particle Coarsening at Gold Electrode/Electrolyte Solution Interfaces Followed by <i>In Situ</i> Scanning Tunneling Microscopy</b> <i>G. Andreasen, M. Nazzarro, J. Ramirez, R. C. Salvezza, A. J. Arvia</i> .....	466
<b>Plasma Treatment Process for Palladium Chemisorption onto Polymers before Electroless Deposition</b> <i>M. Charbonnier, M. Alami, M. Romand</i> .....	472
<b>Three-Dimensional Calculation of Current Distribution in Electrodeposition on Patterned Cathode with Auxiliary Electrode</b> <i>Y.-S. Choi, T. Kang</i> .....	480
<b>Workpiece, Pattern, and Feature Scale Current Distributions</b> <i>B. DeBecker, A. C. West</i> .....	486
<b>Improved Selenization Procedure to Obtain <math>\text{CuInSe}_2</math> Thin Films from Sequentially Electrodeposited Precursors</b> <i>C. Guillén, J. Herrero</i> .....	493
<b>Effect of the Composition of Polypyrrole Substrate on the Electrodeposition of Copper and Nickel</b> <i>M. Hepel, Y.-M. Chen, R. Stephenson</i> .....	498
<b>Mathematical Modeling of Electroless Nickel Deposition at Steady State Using Rotating Disk Electrode</b> <i>Y.-S. Kim, H.-J. Sohn</i> .....	505
<b>Kinetics and Mechanism of Electroless Deposition of Copper</b> <i>K. G. Misbra, R. K. Paramguru</i> .....	510
<b>Effects of Postdeposition Heat-Treatment on Morphology and Microstructure of CdTe Grown by Electrodeposition</b> <i>B. Qi, D. Kim, D. L. Williamson, J. U. Trefny</i> .....	517
<b>Oxidation of n-InP and Indium in the Negative Potential Region at pH 5</b> <i>K. P. Quinlan, P. W. Yip, A. K. Rai, T. N. Wittberg</i> .....	524
<b>Microstructure-Property Relations of Solid Oxide Fuel Cell Cathodes and Current Collectors.</b> <b>Cathodic Polarization and Ohmic Resistance</b> <i>K. Sasaki, J.-P. Wurth, R. Gschwend, M. Gödickemeier, L. J. Gauckler</i> .....	530
<b>Effect of Mask Wall Angle on Shape Evolution during Through-Mask Electrochemical Micromachining</b> <i>R. V. Shenoy, M. Datta</i> .....	544
<b>Electroreduction of <math>\text{C}_{60}</math> in Aprotic Solvents.</b> <b>III. Voltammetric Study, at Microelectrode, of <math>\text{C}_{60}^{n-}</math> (<math>n=0</math> to 4) Solvation in the Absence of Supporting Electrolyte</b> <i>B. Soucaze-Guillous, W. Kutner, M. T. Jones, K. M. Kadish</i> .....	550
<b>The Anodic Behavior of Azide Ions at Carbon Electrodes in Neutral Electrolyte</b> <i>A. Dalmia, S. Wasmus, R. F. Savinell, C. C. Liu</i> .....	556
<b>Electrochemical Behavior of the Manganese-Substituted Nickel Hydroxides</b> <i>L. Guerlou-Demourgues, C. Delmas</i> .....	561
<b>Nonstoichiometry of Sintered Oxide <math>\text{Ca}_{0.9}\text{La}_{0.1}\text{MnO}_{3-\delta}</math> and Its Cathodic Properties in Alkaline Solutions</b> <i>H. Morimoto, M. Kamata, T. Esaka</i> .....	567
<b>A Temperature Study of the Ionic Conductivity of a Hybrid Polymer Electrolyte</b> <i>I. I. Olsen, R. Koksang</i> .....	570

<b>In Situ X-Ray Absorption Near-Edge Spectroscopic Study of the Cathodic Reduction of Artificial Iron Oxide Passive Films</b> <i>P. Schmutki, S. Virtanen, A. J. Davenport, C. M. Vitis</i>	574
<b>Pulsed Electroreduction of CO<sub>2</sub> on Silver Electrodes</b> <i>R. Shiratsuchi, G. Nogami</i>	582
<b>Characterization of Polymer Electrolyte Fuel Cells Using AC Impedance Spectroscopy</b> <i>T. E. Springer, T. A. Zawodzinski, M. S. Wilson, S. Gottesfeld</i>	587
<b>Modeling Lithium Intercalation of Single-Fiber Carbon Microelectrodes</b> <i>M. W. Verbrugge, B. J. Koch</i>	600

## Solid-State Science and Technology

<b>Construction and Working Mechanism of Sulfur Dioxide Sensor Utilizing Stabilized Zirconia and Metal Sulfate</b> <i>Y. Yan, N. Miura, N. Yamazoe</i>	609
<b>An X-Ray Absorption Near-Edge Spectroscopic Study of the Structure of Passive Films on Amorphous Al-Fe-Ce Alloys</b> <i>A. N. Mansour, C. A. Melendres, S. J. Poon, Y. He, G. J. Shiflet</i>	614
<b>Kinetics and Modeling of Wet Etching of Aluminum Oxide by Warm Phosphoric Acid</b> <i>B. Zhou, W. F. Ramirez</i>	619
<b>Growth and Resistivity Behavior of Copper Film by Chemical Vapor Deposition</b> <i>E. S. Choi, S. K. Park, H. H. Lee</i>	624
<b>Repair of Plasma Etch Related Gate Perimeter Damage Using Low Temperature Oxidation</b> <i>R. L. Guldi, D. R. Wyke</i>	628
<b>On the Mechanism of Boron Incorporation during Silicon Epitaxy by Means of Chemical Vapor Deposition</b> <i>H. Kühne, A. Fischer, M. C. Öztürk, M. K. Sangneria</i>	634
<b>Nano-Trenched Local Oxidation of Silicon Isolation Using Island Polysilicon Grains</b> <i>S.-K. Kwon, C. Lim, B.-J. Cho, J.-C. Kim</i>	639
<b>Wettability of Polished Silicon Oxide Surfaces</b> <i>R. R. Thomas, F. B. Kaufman, J. T. Kirleis, R. A. Belsky</i>	643
<b>Silicon Nucleation and Film Evolution on Silicon Dioxide Using Disilane. Rapid Thermal Chemical Vapor Deposition of Very Smooth Silicon at High Deposition Rates</b> <i>K. E. Violette, M. C. Öztürk, K. N. Christensen, D. M. Maher</i>	649
<b>Self-Developing Characteristics of Si Containing Polymers and Their Application to X-Ray Lithography</b> <i>A. Yamaguchi, T. Ogawa, H. Tachibana, H. Oizumi, T. Soga, M. Matsumoto, T. Matsuzaka, E. Takeda</i>	657
<b>Microcrystal Growth on Borophosphosilicate Glass Film during High-Temperature Annealing</b> <i>M. Yoshimaru, H. Wakamatsu</i>	666
<b>Etching Profiles and Neutral Shadowing in Long Trenches</b> <i>B. Abraham-Shrauner, C. D. Wang</i>	672
<b>Effect of Transport Phenomena on Boron Concentration Profiles in Silicon Epitaxial Wafers</b> <i>H. Habuka, M. Mayusumi, H. Tsunoda, M. Katayama</i>	677
<b>Deposition of Tin Oxide into Porous Silicon by Atomic Layer Epitaxy</b> <i>C. Discò, N. Q. Khanh, Z. Horváth, I. Bársony, M. Utraiainen, S. Lehto, M. Nieminen, L. Niinistö</i>	683
<b>Phase Transformation and Lattice Strain of Alpha-AgI Stabilized in Superionic Glass</b> <i>T. Saito, M. Tatsumisago, T. Minami</i>	687
<b>Selective Electroless Nickel Deposition on Patterned Phosphonate and Carboxylate Polymer Films</b> <i>M. L. Shilling, H. E. Katz, F. M. Houliban, S. M. Stein, R. S. Hutton, G. N. Taylor</i>	691

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### Confinement Phenomena in Buried Oxides of SIMOX Structures as Affected by Processing

V. V. Afanas'ev, A. G. Revesz, H. L. Hughes .....695

### Plasma Assisted Dry Etching of Cobalt Silicide for Microelectronics Applications

F. Fracassi, R. d'Agostino, R. Lamendola, A. Filippo, C. Rapisarda, P. Vasquez .....701

### Characteristics of SiOF Films Formed Using Tetraethylorthosilicate and Fluorotriethoxysilane at Room Temperature by Chemical Vapor Deposition

T. Homma .....707

### Control of Surface Concentration of Boron or Phosphorus Employing Ion Shower Doping

A. Kasamatsu, H. Takakubo, K. Shono .....712

### Modeling of the Wear Mechanism during Chemical-Mechanical Polishing

C.-W. Liu, B.-T. Dai, W.-T. Tseng, C.-F. Yeh .....716

### Asymmetric Distribution of Oxygen Concentration in the Si Melt of a Czochralski System

K.-W. Yi, K. Kakimoto, Z. G. Niu, M. Eguchi, H. Noguchi, S. Nakamura, K. Mukai .....722

### Microstructural Properties of Helium Implanted Void Layers in Silicon as Related to Front-Side Gettering

J. W. Medernach, T. A. Hill, S. M. Myers, T. J. Headley .....725

### Atmospheric Pressure Chemical Vapor Deposition of Titanium Nitride from Tetrakis (diethylamido) Titanium and Ammonia

J. N. Musher, R. G. Gordon .....736

### A 0.25 $\mu\text{m}$ MOSFET Technology Using *In Situ* Rapid Thermal Gate Dielectrics

K. X. Zhang, C. M. Osburn, G. Hames, C. Parker, A. Bayoumi .....744

### Dissolution Windows for Wet Chemical Processing of Silicon and Silicon Dioxide: Potential-pH Diagrams for the Si-F-H<sub>2</sub>O System

K. Osseo-Asare, D. Wei, K. K. Mishra .....749

### Comparison of Dry Etching Techniques for III-V Semiconductors in CH<sub>4</sub>/H<sub>2</sub>/Ar Plasmas

S. J. Pearton, J. W. Lee, E. S. Lambers, C. R. Abernathy, F. Ren, W. S. Hobson, R. J. Shul .....752

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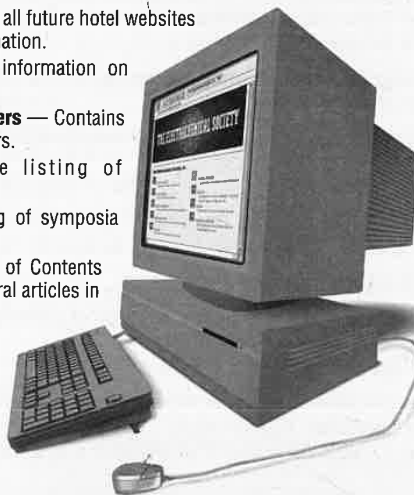
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# Effect of Mask Wall Angle on Shape Evolution during Through-Mask Electrochemical Micromachining

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## ABSTRACT

A mathematical model to predict shape evolution during through-mask electrochemical micromachining (EMM) has been developed. Boundary element method has been used to solve the Laplace equation for electric potential with appropriate boundary conditions that describe the metal dissolution process under ohmic control. The influence of mask wall angle on shape of the evolving cavity, current distribution within the cavity and etch factor have been determined. For mask wall angles less than  $90^\circ$ , the etch factor increased due to the shadowing effect of the mask, whereas the etch factor decreased for mask wall angles greater than  $90^\circ$ . The influence of mask wall angle has been found to diminish with increasing metal film thickness.

Electrochemical micromachining (EMM) is receiving increasing attention in microfabrication for patterning, shaping, and finishing.<sup>1</sup> In through-mask EMM, a photoresist patterned metal workpiece is made an anode in an electrochemical cell such that the exposed metal surface is removed by high rate anodic metal dissolution. The through-mask EMM can involve etching of the metal workpiece either from a single side or from both sides simultaneously. EMM of metal films supported by insulating substrates involve single-sided through-mask metal removal. The isotropic nature of the metal removal process leads to undercutting of the mask. *A priori* knowledge of the metal removal rates and the undercutting of the photoresist is, therefore, essential in designing the photoresist mask.

In through-mask EMM, the metal dissolution takes place at the electrode surface that lies at the bottom of a cavity created by the photoresist mask. The current distribution at the electrode is thus dictated by the photoresist artwork parameters. Any variations in these parameters affects the current distribution at the metal surface and the spatial distribution of the metal removal rate. This has led to several investigations on the effect of photoresist thickness and spacing on shape evolution during through-mask EMM.<sup>2-5</sup> However, none of these investigations considered the variation in the mask wall angle and its influence on the shape evolution. On the other hand, small changes in exposure and development conditions during photoresist processing may lead to variations in the photoresist wall angle. These variations may lead to different current distribution at the dissolving metal surface.

Diem, *et al.*<sup>6</sup> investigated the influence of small variations in the wall angle on current distribution and estimated machining accuracy essential for making a recessed disk electrode. The results showed that an accuracy of  $0.5^\circ$  in the right angle between the insulator and the disk electrode was required to avoid any significant error in the measured current. The geometry used by Diem *et al.* is similar to that of through-mask EMM. However, in through-mask EMM, it is essential to consider the current distribution both at the initial electrode surface and within the evolving cavity.

In recent studies, the application of through-mask EMM has been demonstrated in the fabrication of several electronic components requiring different metal wall profiles. Examples include: ink jet nozzle plates containing high precision V-shaped nozzles, metal masks, cone connectors, and patterns of metal films on insulators.<sup>7-11</sup> The metal wall profile required for these components varied from tapered metal walls to straight metal walls. In all these studies, EMM has been demonstrated as an effective method for fabricating microelectronic components with significant cost and environmental advantages over competing fabrication technologies. For a wider application of

EMM, the predictability and control of metal wall profile evolution and undercut are of particular interest. In this paper, the influence of the mask wall angle on the current distribution, the shape of the evolving cavity, and the etch factor have been investigated. The principal objective is to determine how deviations ( $\pm 10^\circ$ ) in the mask wall angle affect the directionality of through-mask EMM.

## Model Development

Figure 1 shows a scheme of the patterned electrode that has been considered for this investigation. The patterned electrode consists of a metal film of a finite thickness,  $b$ , which is partially covered with an inert photoresist mask of thickness,  $h$ . The pattern involves equally spaced straight lines of width,  $2L$ , that are separated by a spacing of  $2a$ . The angle between the photoresist sidewall and the metal electrode surface is  $\beta$ .

The parameters that characterize the shape evolution during through-mask EMM are (Fig. 1): (i) aspect ratio,  $h/L$ , (ii) spacing to opening ratio,  $a/L$ , (iii) metal film thickness ratio,  $b/L$ , and (iv) mask wall angle,  $\beta$ . The aspect ratio, spacing to opening ratio, and the mask wall angle influence the current distribution at the electrode. On the other hand, the metal film thickness ratio determines the extent to which EMM must proceed before the underlying insulator is exposed. The influence of these parameters on the undercut,  $U$ , and the etch factor are of interest. The etch factor is defined as the ratio of the maximum etched depth to the undercut,  $(d/U)$ . Once the insulator is exposed, metal dissolution continues in the lateral direction leading to a change in metal wall angle,  $\chi$ . Fine line through-mask EMM of metal films on insulator requires minimized undercut (hence increased etch factor), and straight walls. In this investigation, the influence of the mask wall angle,  $\beta$ , on the etch factor has been evaluated.

**Assumptions.**—The following assumptions have been made in the development of the model for shape evolution during through-mask EMM: (i) The shape evolution has been investigated at a patterned electrode consisting of equally spaced patterns (lines). This facilitated the use of the lines of symmetry to limit the computations to a domain defined by the electrode, the photoresist walls, the

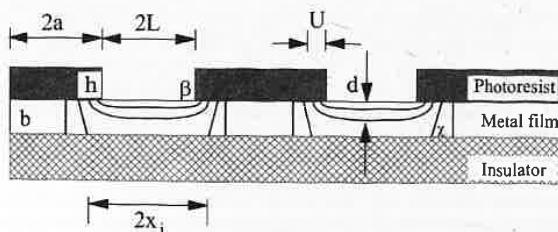


Fig. 1. Schematic diagram of a patterned metal film supported on an insulator.

\* Electrochemical Society Active Member.

lines of symmetry and a virtual cathode; (ii) The current distribution at the metal surface has been determined solely by the ohmic effects and the electrodes were defined as equipotential surfaces. Thus, a primary current distribution has been assumed. This assumption is justified as the EMM is at relatively high current densities involving low Wagner numbers; (iii) Faraday's law has been used to determine the rate at which the anode surface recedes. A constant current efficiency during the EMM process has been assumed; and (iv) The progress of metal dissolution has been followed in terms of the ratio of the maximum etched depth and the feature half-width ( $d/L$ ).

**Model equations.**—The current distribution has been obtained by solving the distribution of the electric potential in the electrolyte as governed by Laplace's equation

$$\nabla^2 \phi = 0 \quad [1]$$

Since the kinetic resistances at the electrodes have been neglected, the boundary condition at the anode is

$$\phi = V_a \quad [2]$$

and at the cathode is

$$\phi = 0 \quad [3]$$

The potential gradients across the various lines of symmetry and insulators have been set to zero

$$\frac{\partial \phi}{\partial n} = 0 \quad [4]$$

The current distribution at the anode has been combined with Faraday's law to determine the evolution of the metal surface. The rate,  $r$ , at which the anodic surface recedes is

$$r = \frac{M\theta}{nF\rho} i \quad [5]$$

where  $M$  is the molecular weight of the metal,  $n$  is the metal dissolution valence,  $\rho$  is the density of the metal film,  $F$  is Faraday's constant, and  $\theta$  is the current efficiency of metal dissolution which is assumed to be constant at 100%.

**Method of solution.**—Solution of the shape evolution problem requires the use of numerical techniques. The various numerical techniques available to solve the current distribution problems can be broadly divided into the domain based techniques such as finite difference and finite elements methods and the boundary based techniques such as the boundary element method. Although, finite difference method is easy to implement in regular geometries, the irregular shapes encountered in solving the shape evolution problems cannot be easily handled. The finite element method is more suitable for such problems. However, the domain based techniques require that the potential distribution over the entire domain be solved. Further, this has to be repeated at each time step to determine the shape of the evolving cavity.

The boundary element method,<sup>12</sup> on the other hand, has a significant advantage over the domain based techniques in solving Laplace's equation. The boundary element method can be used to determine the current distribution at the electrodes without solving the potential distribution over the entire domain. This presents a significant savings in computations in the shape evolution problems where the current distribution has to be repeatedly determined. Hence, boundary element method<sup>12</sup> has been used in this investigation. The current density at the anode has been determined by solving Laplace's equation, Eq. 1, and using boundary conditions, Eq. 2-4. The anode surface has then been displaced proportionally to the current density,  $i$ , using Faraday's Law (Eq. 5) to predict the shape of the evolving cavity. The details on implementation of the numerical procedure have been discussed in the Appendix.

## Results and Discussion

In order to minimize the effect of the geometry other than the mask wall angle, a case of recessed electrode has

been considered. For straight vertical mask walls ( $\beta = 90^\circ$ ) uniform current distribution is obtained for aspect ratio ( $h/L$ ) of 1.0 or greater.<sup>8</sup> Hence, an aspect ratio of 2.5 has been chosen along with a spacing to opening ratio of 4.

**Current distribution.**—Figure 2 shows the normalized current distribution at the initial patterned electrode surface for various mask wall angles. For straight vertical mask walls, ( $\beta = 90^\circ$ ), the current distribution at the initial electrode is very uniform. However, deviation in the mask wall angle,  $\beta$ , from the straight vertical walls significantly alters the current distribution at the initial metal surface. For  $\beta < 90^\circ$ , the normalized current density at the center of the feature is greater than 1 and it decreases as the intersection of the insulating mask and the metal electrode is approached. The current density at the intersection, for  $\beta < 90^\circ$ , is equal to zero. Conversely, for  $\beta > 90^\circ$ , the normalized current density at the center of the feature is less than 1 and it increases as the intersection of the insulating mask and the metal electrode is approached. The current density at the intersection, for  $\beta > 90^\circ$ , is infinite. This is consistent with current distribution along an electrode near the intersection of an electrode and an insulator.

The current distribution at the initial electrode surface shown in Fig. 2 is extremely sensitive to the mask wall angle. Even small changes in the mask wall angle lead to significantly different current distributions along the electrode surface. In the following, the current distribution at various stages of the evolving cavity has been investigated.

Figure 3 shows the normalized current distribution along the evolving metal surface for a mask wall angle of  $80^\circ$ . The parameter,  $S/S_L$ , is a normalized distance measured from the center of the feature. The variable,  $S$ , is the distance along the evolving metal surface measured from the center of the feature and  $S_L$  is the half-length of the evolving metal surface. The normalized arc length,  $S/S_L$ , of 1.0 corresponds to the point of intersection

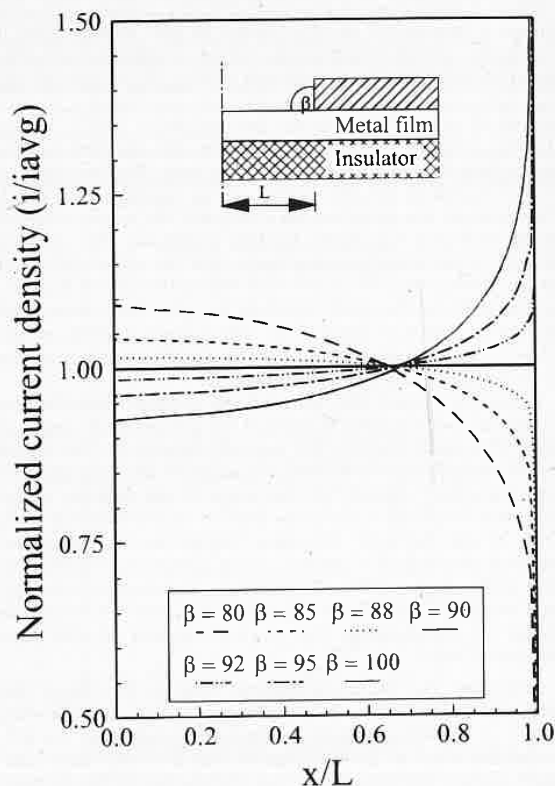


Fig. 2. Normalized current distribution at the initial metal surface for various mask wall angles,  $\beta$ .



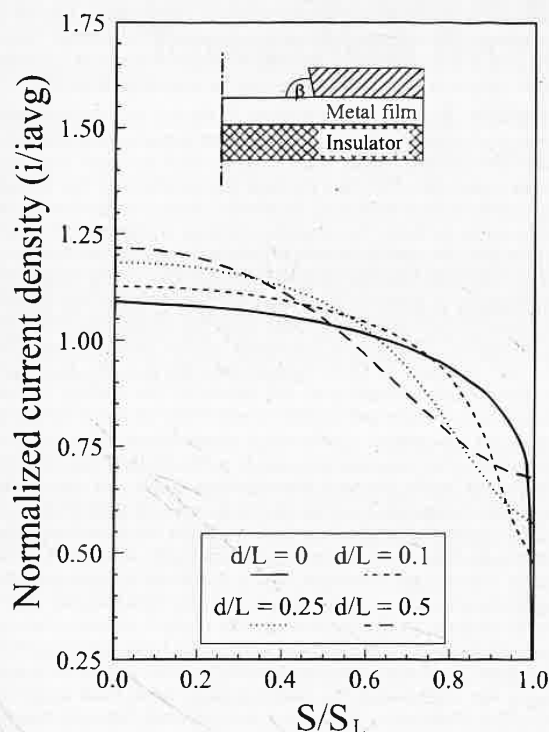


Fig. 3. Normalized current distribution along the evolving metal surface at different etched depths for mask wall angle,  $\beta = 80^\circ$ .

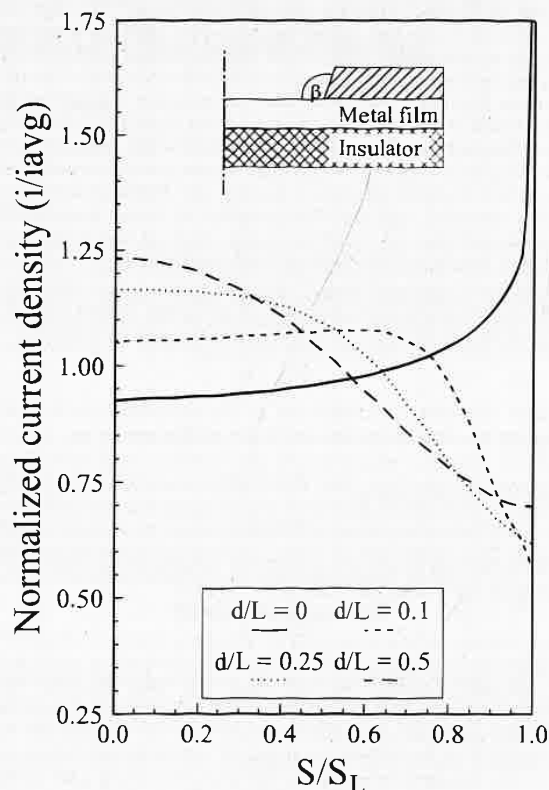


Fig. 4. Normalized current distribution along the evolving metal surface at different etched depths for mask wall angle,  $\beta = 100^\circ$ .

between the metal electrode and the photoresist mask. The current distribution at the initial metal surface ( $d/L = 0$ ) shows a maximum at the center of the feature and it decreases as the mask/anode edge is approached. This leads to a higher metal removal rate at the center of the feature as compared to the edge, thus providing a certain degree of anisotropy during through-mask EMM. Under strictly primary current distribution, the current density at the edge of the feature is initially zero. This would lead to no undercut as the initial metal surface is etched. However, as the metal surface recedes, the angle between mask wall and the metal surface increases. The current density at the edge becomes finite and the undercutting of the photoresist takes place.<sup>a</sup> The redistribution of the current density as the cavity evolves has also been shown. As the metal removal progresses, the current density at the edge becomes finite and the current distribution across the electrode becomes more uniform.

Figure 4 shows the normalized current distribution along the evolving metal surface for a mask wall angle of  $100^\circ$ . The maximum in the current density at the initial metal surface ( $d/L = 0$ ) is at the edge of the feature. The higher current density at the edge of the feature is not desirable because it leads to higher lateral etching than that in the vertical direction. However, as the metal removal proceeds, the undercutting results in a redistribution of the current. The maximum in the current distribution begins to shift from the edge and moves toward the center of the feature. The current density at the edge becomes finite.

**Shape of the evolving cavity.**—Figure 5a shows the shape of the metal surface evolving for initial mask wall angles of  $80^\circ$ ,  $90^\circ$  (straight vertical walls), and  $100^\circ$  for different amounts of etched depths. For  $\beta \leq 90^\circ$ , the maximum etched depth is always at the center of the feature.

<sup>a</sup> In practice, the finite resistance of the electrode kinetics would tend to smooth the initial current distribution and the undercutting would initiate even at the initial metal surface.

For  $\beta > 90^\circ$ , the initial maximum etched depth is away from the center of the feature, as shown in Fig. 5b. The maximum etched depth moves toward the center of the feature as the shape evolves during EMM. An analysis of the evolving cavity shape indicates that for the same etched depth,  $d$ , the undercut depends on the mask wall angle. The undercut for mask wall angle,  $\beta = 80^\circ$  is less than that for  $\beta = 90^\circ$ , which in turn is less than that for  $\beta = 100^\circ$ . The reduction in undercut in acute angled masks leads to higher etch factors, thus providing a certain amount of directionality in the metal removal process. In the following, the effectiveness of through-mask EMM has been further investigated in terms of the etch factor.

**Etch factor.**—Figure 6 shows the etch factor during through-mask EMM for an aspect ratio,  $(h/L)$ , of 2.5. For masks with straight vertical walls ( $\beta = 90^\circ$ ), the etch factor for a recessed feature starts around 2.0 and then decreases as EMM proceeds. For mask wall angles less than  $90^\circ$ , the etch factor is higher than cases with straight vertical mask walls. The shadowing effect of the mask reduces the current density at the edge of the feature. Hence, the spatial distribution of the etch rate, near the edge of the feature is lower than that at the center of the feature. This reduces the undercut resulting in the increased etch factor. However, as the metal removal proceeds the difference in the etch factor between  $90^\circ$  and acute angled masks decreases. This is a result of the redistribution of the current within the evolving cavity that leads to the diminishing influence of the mask wall angle.

For mask wall angles greater than  $90^\circ$ , the etch factor is less than that for straight vertical mask walls. The current concentration near the intersection of the mask and the metal line leads to higher undercuts and lower etch factors. However, as the EMM proceeds, the difference in the etch factor for mask wall angles greater than  $90^\circ$  and straight vertical walls decreases. Again, the redistribution

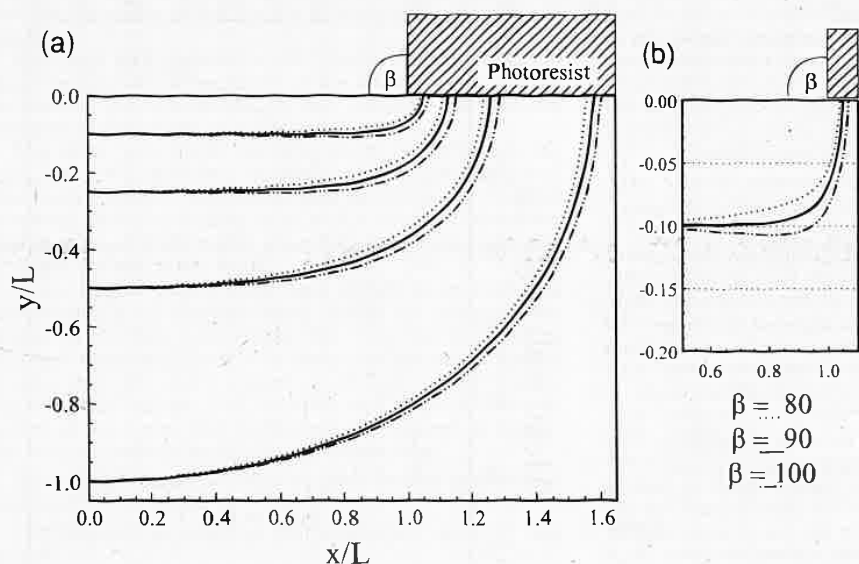


Fig. 5. (a) Shape of the evolving cavity for various mask wall angles,  $\beta$ ; (b) the axes have been expanded to highlight the effect of mask wall angle during initial stages of metal removal.

of the current within the evolving cavity plays a role in diminishing the influence of the mask wall angle.

The discussion so far has been limited to cases where the maximum etched depth is less than the metal film thickness. In such cases, the metal removal takes place both in the vertical and the lateral directions. The degree of anisotropy is determined by the ratio of the metal removal in the two directions, *i.e.* by the etch factor. In single-sided through-mask EMM, the metal removal exposes the insulator under the metal film once the maximum etched depth exceeds the metal film thickness. In a double-sided through-mask EMM, this results in a through hole in the

workpiece. In both cases, further metal removal leads to the movement of the metal surface in the lateral direction under the photoresist mask. The extent to which the metal removal is carried out then depends on the desired metal wall profile.

**Metal wall profile evolution.**—Figure 7 shows the evolution of the metal wall profile for a mask angle of 90°. The shape of the evolving cavity has been shown starting from the point just prior to the exposure of the insulator under the metal film. At the point where the normalized maximum etched depth ( $d/L$ ) is equal to the metal film thickness ratio ( $b/L$ ), the metal surface fits an elliptical curve. As the metal removal progresses, the insulator under the metal film is exposed. The metal film closer to the insulator is removed faster than that under the photoresist and the metal film profile evolves toward a straight wall. The evolution of the metal wall profile for various mask wall angles can be compared in terms of the metal wall angle,  $\chi$ , which is defined as

$$\tan \chi = \frac{b}{(L + U - \chi_1)} \quad [7]$$

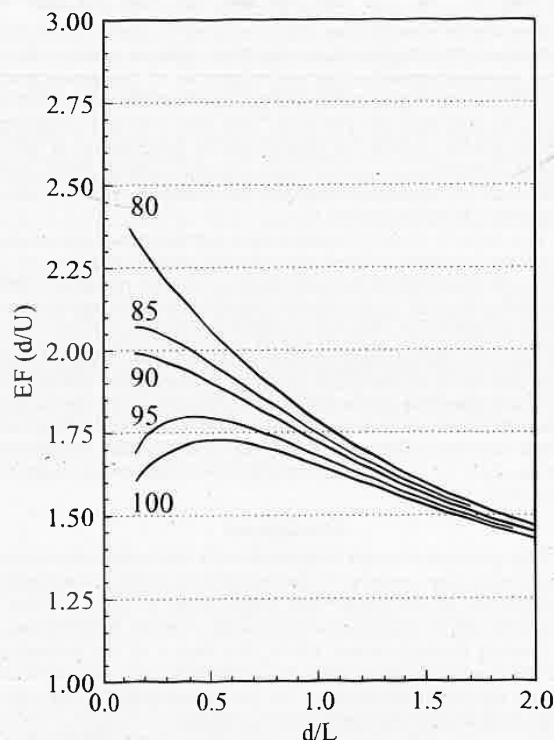


Fig. 6. Etch factor as a function of the etched depth for various mask wall angles,  $\beta$ .

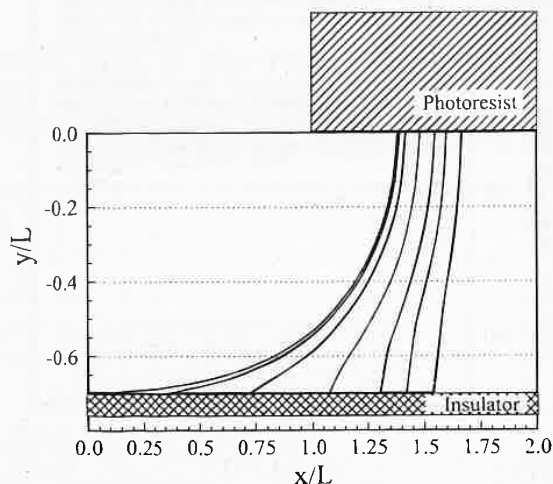


Fig. 7. Evolution of the metal wall profile after the underlying insulator is exposed.

where  $L$  is the feature half-length,  $U$  is the undercut, and  $x_i$  is the half-length of the exposed insulator. The extent of the metal removal necessary to obtain a certain metal wall angle can be expressed in terms of the ratio of undercut to metal film thickness. In the following, the influence of the mask wall angle on the metal wall angle,  $\chi$ , for different metal film thickness ratios has been investigated.

**Lateral metal removal in thin films ( $b/L \leq 1$ ).**—The evolution of the metal wall angle has been investigated for metal film thickness ratio of 0.2 and 0.7. Figure 8 shows the metal wall angle as EMM progresses for a metal film thickness ratio of 0.2 and mask wall angles for 80°, 90°, and 100°. The general trend of the metal wall angle evolution for all three mask wall angles is the same. The metal wall angle is shown from the point when the bottom insulator is exposed to the point where the metal wall angle is greater than 80°. Initially, the metal wall angle,  $\chi$ , increases rapidly but the rate of change of the metal wall angle decreases as the metal removal progresses. The undercut essential to obtain a desired wall profile is lower in acute angled masks than in right angled or obtuse angled masks. This indicates that the directionality of the EMM process can be improved by the use of acute angled masks when the film thickness ratio is low.

Figure 9 shows the metal wall angle as EMM progresses for a metal film thickness ratio of 0.7 and mask wall angles for 80°, 90°, and 100°. The metal wall angle evolution is similar to that observed for the metal film thickness of 0.2. Initially, the metal wall angle increases rapidly and the rate of increase slows down as the metal wall angle approaches 90° asymptotically. Figure 8 also shows that the differences in the metal wall angle for various mask wall angles are significantly less for metal film thickness ratio of 0.7, than those observed for 0.2. The influence of the mask wall angle has been shown to decrease with increasing metal film thickness.

**Lateral metal removal in thick films ( $b/L \geq 1$ ).**—The influence of the mask wall angle on the etch factor is minimal as shown in Fig. 6. It is also an insignificant factor in

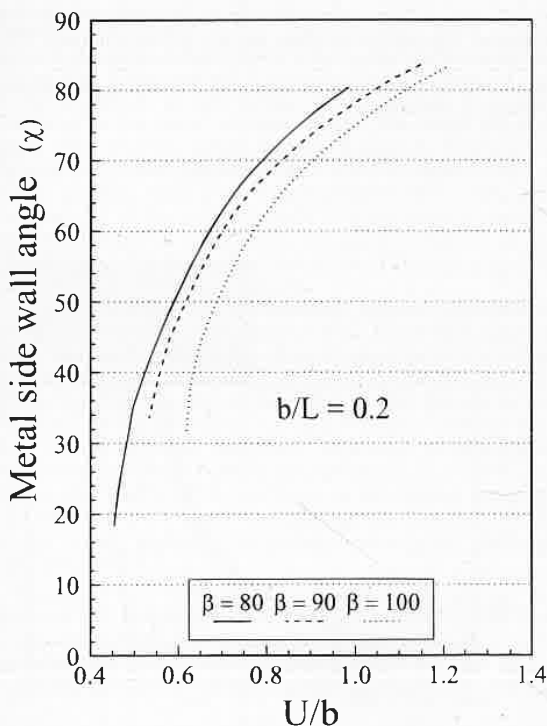


Fig. 8. Metal wall angle evolution for various mask wall angles,  $\beta$  for metal film thickness ratio of 0.2.

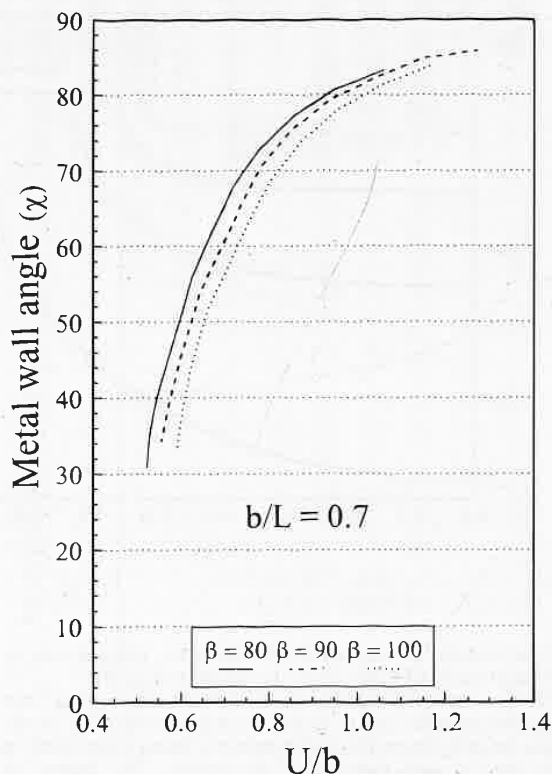


Fig. 9. Metal wall angle evolution for various mask wall angles,  $\beta$  for metal film thickness ratio of 0.7.

the evolution of the metal wall profile. Thus, there are no gains to be achieved in directionality by varying the mask wall angle in through-mask EMM of thick metal films.

The above results can also be used to understand the influence of complex resist profiles such as a resist foot and rounded profile. The investigation of the resist foot would involve two additional dimensionless parameters used to characterize the foot. The effect of the rounded resist profile would be important in machining of thin metal films ( $b/L \leq 1$ ). Whereas, for thick metal films, the effect of the rounded profile would diminish with increasing metal film thickness.

The results of the present study indicate that the mask wall angle can substantially impact undercutting during through-mask EMM in early stages of metal removal. This behavior can be particularly useful in patterning of features in thin films. The photoresist mask angle of less than 90° can be used to reduce the undercut and improve the directionality of the EMM process. However, the influence of the mask wall angle diminishes with an increase in the metal film thickness ratio. This impacts the etching of deep cavities. In cases with high metal film thickness ratio, ( $b/L \geq 1$ ), the influence of the mask wall angle is minimal.

### Conclusions

The primary current distribution at the initial electrode surface is very sensitive to the mask wall angle. Even small deviations in the mask wall angle from straight vertical walls result in drastic changes in the current distribution.

During through-mask EMM, the shape of the evolving cavity causes significant redistribution of the current along the electrode surface. As the shape evolves, the current distribution becomes more uniform.

For mask wall angle of  $\beta > 90^\circ$ , the current distribution at the initial surface has a maximum at the edge of the feature. The maximum in the current distribution moves



toward the center of the feature as the metal removal progresses.

For mask wall angle of  $\beta < 90^\circ$ , the current distribution has a maximum at the center of the feature. As the EMM proceeds, the maximum in the current distribution remains at the center of the feature.

The mask wall angle has been shown to influence the etch factor. The influence is greatest in the initial stages of the metal removal and diminishes as the metal removal proceeds. With increasing etch depth, the etch factor for different mask wall angles approaches the etch factor for straight vertical mask walls.

Acute angled masks have been shown to improve the directionality of through-mask EMM by reducing the undercut for thin metal films. The undercut to obtain a desired metal wall profile is lower for the acute angled masks than for right angled or obtuse angled masks. However, the influence of the mask wall angle on the evolution of the metal wall profile has been shown to diminish with increasing metal film thickness ratio.

Manuscript submitted Mar. 9, 1995; revised manuscript received Oct. 1, 1995.

IBM assisted in meeting the publication costs of this article.

#### APPENDIX

The current distribution at the anode has been determined by solving the model equations using boundary element method.<sup>12</sup> The boundaries have been divided into quadratic elements by equally spaced nodes. The number of nodes have been increased till the resulting changes in the current density are negligible. This approach has been found to be sufficient to determine the current distribution for  $\beta = 90^\circ$ . However, the current distribution near the anode/mask intersection has been found to change significantly as  $\beta$  deviates from  $90^\circ$ . This nonuniform current distribution problem has been solved by placing more nodes near the anode/mask intersection. The distribution of the nodes along the anode has been varied till the current density distribution near the mask/anode intersection for various values of  $\beta$  satisfy the the following asymptotic expression<sup>13</sup>

$$i(R) \propto R^{(\pi/2\beta-1)} \quad [A-1]$$

where  $R$  is the distance from the mask/anode intersection.

At each time step, the anode surface has been displaced proportionally to the current density,  $i$ . The electrode surface at the center of the feature has been displaced vertically by a distance of 0.005-0.001 times the electrode half length,  $L$ . The time steps have been increased as the shape evolution progressed. The nodes on the newly generated surface have been repositioned. Nodes are added to maintain the initial internodal spacing. The step size used for shape evolution has been varied till the evolving profiles are independent of the step sizes.

In addition, the model has also been solved by formulating the model equations in terms of stream functions.<sup>9</sup> The advantage of using stream functions is that the current distributions does not show numerical instabilities near the anode/insulator edge. In the present study, the current distribution at the initial electrode surface has been determined by using stream functions whereas the current distribution on evolving surfaces have been determined by using the potential. The shape evolution and etch factors predicted by using either of the two methods (stream functions or potential) are identical.

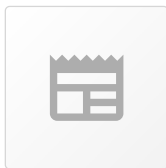
#### LIST OF SYMBOLS

$a$	distance between photoresist edge and line of symmetry, cm
$b$	thickness of metallic film, cm
$b/L$	metal film thickness ratio
$d$	maximum etched depth, cm
$d/L$	normalized etched depth
$EF$	etch factor ( $d/U$ )
$F$	faraday constant, 96,500 C/eq
$h$	photoresist mask height, cm
$h/L$	aspect ratio
$i$	current density, A/cm <sup>2</sup>
$L$	half-length of the feature, cm
$M$	molecular weight of the metal, g/mol
$n$	valence of metal dissolution
$r$	material removal rate, cm/s
$R$	distance from the mask/anode intersection, cm
$S$	distance along the evolving cavity measured from the center of the feature, cm
$S_L$	half-length of metal electrode in an evolving cavity, cm
$U$	undercut, cm
$V_a$	potential of the anode, V
$x_i$	half-length of exposed insulator, cm
Greek	
$\beta$	mask wall angle, degrees
$\chi$	metal wall angle, degrees
$\phi$	potential, V
$\rho$	density of material, g/cm <sup>3</sup>
$\theta$	current efficiency of metal dissolution

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##### Indexes

[v.99/108\(1952/1961\)](#)[v.109/118\(1962/1971\)](#)

## ○ Publication Details

**FORMAT**

Journals, Magazines, Newspapers

**LANGUAGE**

English

**CONTRIBUTORS**[Electrochemical Society](#)**PUBLICATION**

New York, N.Y. : Electrochemical Society, 1948-

**PUBLICATION DATES**

Vol. 93, no. 1 (Jan. 1948)-

**PHYSICAL DETAILS**

volumes : illustrations, portraits ; 23-29 cm

**ISSNS**

1945-7111, 0013-4651

**OCLC**

ocm60639352, ocm01029376

**FINDING AIDS**

Vols. 93 (1948)-98 (1951), (Includes index to its Transactions. v. 81 (1942)-92 (1947), 1 v.; Vols. 99 (1952)-108 (1961), 1 v.; Vols. 109 (1962)-118 (1971).

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## ○ Notes

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Published: Manchester, NH, &lt;1980-&gt;; Pennington, NJ, &lt;2004-&gt;

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- 321 \$aMonthly,\$b-2013
- 362 1\_ \$aPrint began with vol. 93, no. 1 (Jan. 1948).
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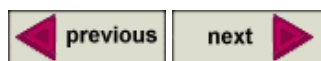
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**Serial Publication Year:** 1996

**Serial Key Title:** Journal of the Electrochemical Society

**Imprint:** Manchester, N. H. : The Society.

**ISSN:** 0013-4651

**Description:** print material.

**Frequency:** Monthly.

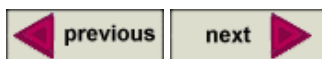
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# APPENDIX D

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VOLUME 28

NUMBER 11

EDLEDZ

(ISSN 0741-3106)

9844848 08/11/07 BOSTON SPA L823 780  
IEEE ELECTRON DEVICE LETTERS.



4362.922800  
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1

## LETTERS

### Compound Semiconductor Devices

- Submicrometer Inversion-Type Enhancement-Mode InGaAs MOSFET With Atomic-Layer-Deposited  $\text{Al}_2\text{O}_3$  as Gate Dielectric ..... Y. Xuan, Y. Q. Wu, H. C. Lin, T. Shen, and P. D. Ye 935
- Remarkable Reduction of On-Resistance by Ion Implantation in GaN/AlGaIn/GaN HEMTs With Low Gate Leakage Current ..... K. Nomoto, T. Tajima, T. Mishima, M. Satoh, and T. Nakamura 939
- The Leakage Current of the Schottky Contact on the Mesa Edge of AlGaIn/GaN Heterostructure ..... C. Xu, J. Wang, H. Chen, F. Xu, Z. Dong, Y. Hao, and C. P. Wen 942
- Power Performance of AlGaIn/GaN HEMTs Grown on SiC by Ammonia-MBE at 4 and 10 GHz ..... C. Poblenz, A. L. Corrión, F. Recht, C. S. Suh, R. Chu, L. Shen, J. S. Speck, and U. K. Mishra 945
- Comparison of GaN HEMTs on Diamond and SiC Substrates ..... J. G. Felbinger, M. V. S. Chandra, Y. Sun, L. F. Eastman, J. Wasserbauer, F. Failli, D. Babic, D. Francis, and F. Ejeckam 948

### Materials and Processing

- A New Nonvolatile Bistable Polymer-Nanoparticle Memory Device ..... H.-T. Lin, Z. Pei, J.-R. Chen, G.-W. Hwang, J.-F. Fan, and Y.-J. Chan 951
- Good High-Temperature Stability of TiN/ $\text{Al}_2\text{O}_3$ /WN/TiN Capacitors ..... T.-M. Pan, C.-I. Hsieh, T.-Y. Huang, J.-R. Yang, and P.-S. Kuo 954
- Demonstration of Low  $V_t$  Ni-FUSI N-MOSFETs With SiON Dielectrics by Using a  $\text{Dy}_2\text{O}_3$  Cap Layer ..... H. Y. Yu, S. Z. Chang, A. Veloso, A. Lauwers, C. Adelman, B. Onsia, P. Lehen, T. Kauerauf, S. Brus, K. M. Yin, P. Absil, and S. Biesemans 957

(Contents Continued on Page 933)



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Digital Object Identifier 10.1109/LED.2007.910657

Young's Modulus Measurements in Standard IC CMOS Processes Using MEMS Test Structures . . . . .	960
..... J. C. Marshall, D. L. Herman, P. T. Vernier, D. L. DeVoe, and M. Gaitan	
Metal–Oxide–High- $\kappa$ Dielectric–Oxide–Semiconductor (MOHOS) Capacitors and Field-Effect Transistors for Memory Applications . . . . .	964
..... H. Hsu, I. Y. Chang, and J. Y. Lee	
Current-Dependent Switching Characteristics of PI-Diphenyl Carbamyl Films . . . . .	967
..... M. Kim, S. Choi, M. Ree, and O. Kim	
Improvement of the Conversion Performance of a Resonating Multimode Microelectromechanical Mixer-Filter Through Parametric Amplification . . . . .	970
..... M. Koskenvuori and I. Tittonen	
A Phase Change Memory Compact Model for Multilevel Applications . . . . .	973
..... D. Ventrice, P. Fantini, A. Redaelli, A. Pirovano, A. Benvenuti, and F. Pellizzer	
Effects of Sulfur Passivation on Germanium MOS Capacitors With HfON Gate Dielectric . . . . .	976
..... R. Xie and C. Zhu	
Achieving Low- $V_T$ Ni-FUSI CMOS by Ultra-Thin Dy <sub>2</sub> O <sub>3</sub> Capping of Hafnium Silicate Dielectrics . . . . .	
..... A. Veloso, H. Y. Yu, S. Z. Chung, C. Adelmann, B. Onsia, S. Brus, M. Demand, A. Lauwers, B. J. O'Sullivan, R. Singanamalla, G. Pourtois, P. Lehen, S. Van Elshocht, K. De Meyer, M. Jurczak, P. P. Absil, and S. Biesemans	980
<b>Optoelectronics</b>	
Impact of Local Strain From Selective Epitaxial Germanium With Thin Si/SiGe Buffer on High-Performance p-i-n Photodetectors With a Low Thermal Budget . . . . .	984
..... W. Y. Loh, J. Wang, J. D. Ye, R. Yang, H. S. Nguyen, K. T. Chua, J. F. Song, T. H. Loh, Y. Z. Xiong, S. J. Lee, M. B. Yu, G. Q. Lo, and D. L. Kwong	
<b>Silicon Alloys and Thin Film Devices</b>	
On the Low-Frequency Noise of pMOSFETs With Embedded SiGe Source/Drain and Fully Silicided Metal Gate . . .	987
..... E. Simoen, P. Verheyen, A. Shickova, R. Loo, and C. Claeys	
Improved Electrical Characteristics and Reliability of MILC Poly-Si TFTs Using Fluorine-Ion Implantation . . . . .	990
..... C.-P. Chang and Y. S. Wu	
A Simple Spacer Technique to Fabricate Poly-Si TFTs With 50-nm Nanowire Channels . . . . .	993
..... C.-W. Chang, C.-K. Deng, H.-R. Chang, C.-L. Chang, and T.-F. Lei	
Hot-Carrier Effects in Strained n-Channel Transistor With Silicon–Carbon (Si <sub>1-y</sub> C <sub>y</sub> ) Source/Drain Stressors and Its Orientation Dependence . . . . .	996
..... K.-W. Ang, C. Wan, N. Balasubramanian, G. S. Samudra, and Y.-C. Yeo	
Improving the Electrical Properties of NILC Poly-Si Films Using a Gettering Substrate . . . . .	1000
..... C.-M. Hu, Y. S. Wu, and C.-C. Lin	
Amorphous-Silicon Thin-Film Transistors Fabricated at 300 °C on a Free-Standing Foil Substrate of Clear Plastic 1200-V 5.2-m $\Omega$ · cm <sup>2</sup> 4H-SiC BJTs With a High Common-Emitter Current Gain . . . . .	1004
..... K. H. Cherenack, A. Z. Kattamis, B. Hekmatshoar, J. C. Sturm, and S. Wagner	
..... H.-S. Lee, M. Domeij, C.-M. Zetterling, M. Östling, F. Allerstam, and E. Ö. Sveinbjörnsson	1007
High-Performance Short-Channel Double-Gate Low-Temperature Polysilicon Thin-Film Transistors Using Excimer Laser Crystallization . . . . .	1010
..... C.-C. Tsai, K.-F. Wei, Y.-J. Lee, H.-H. Chen, J.-L. Wang, I.-C. Lee, and H.-C. Cheng	
N-Channel (110)-Sidewall Strained FinFETs With Silicon–Carbon Source and Drain Stressors and Tensile Capping Layer . . . . .	1014
..... T.-Y. Liow, K.-M. Tan, R. T. P. Lee, C.-H. Tung, G. S. Samudra, N. Balasubramanian, and Y.-C. Yeo	
<b>Silicon and Elemental Semiconductor Devices</b>	
The Origin of Electron Mobility Enhancement in Strained MOSFETs . . . . .	1018
..... G. Hadjisavvas, L. Tsetseris, and S. T. Pantelides	
CMOS Inverter Based on Gate-All-Around Silicon-Nanowire MOSFETs Fabricated Using Top-down Approach . . .	1021
..... S. C. Rustagi, N. Singh, W. W. Fang, K. D. Buddharaju, S. R. Omampuliyur, S. H. G. Teo, C. H. Tung, G. Q. Lo, N. Balasubramanian, and D. L. Kwong	
Effect of Substrate Parasitic Inductance on Silicon-Based Transmission Lines and On-Chip Inductors . . . . .	1025
..... F. Huang, J. Lu, Y. Zhu, N. Jiang, X. Wang, and Y. Chi	
Design of On-Chip Transformer With Various Coil Widths to Achieve Minimal Metal Resistance . . . . .	1029
..... H.-M. Hsu and C.-W. Tseng	
OFF-State Avalanche-Breakdown-Induced ON-Resistance Degradation in Lateral DMOS Transistors . . . . .	1033
..... J. F. Chen, J. R. Lee, K.-M. Wu, T.-Y. Huang, C. M. Liu, and S. L. Hsu	
On the Apparent Mobility in Nanometric n-MOSFETs . . . . .	1036
..... M. Zilli, D. Esseni, P. Palestri, and L. Selmi	



Mobility Modeling and Its Extraction Technique for Manufacturing Strained-Si MOSFETs . . . . .	1040
. . . . . J.-S. Wang, W. P.-N. Chen, C.-H. Shih, C. Lien, P. Su, Y.-M. Sheu, D. Y.-S. Chao, and K.-I. Goto	
Improved Electrical Characteristics of Ge-on-Si Field-Effect Transistors With Controlled Ge Epitaxial Layer Thickness on Si Substrates . . . . .	1044
. . . . J. Oh, P. Majhi, H. Lee, O. Yoo, S. Banerjee, C. Y. Kang, J.-W. Yang, R. Harris, H.-H. Tseng, and R. Jammy	
A Novel Single Polysilicon EEPROM Cell With a Polyfinger Capacitor . . . . .	1047
. . . . K.-Y. Na, Y.-S. Kim, and Y.-S. Kim	
<hr/>	
IEEE ELECTRON DEVICES SOCIETY MEETINGS CALENDAR . . . . .	1050
<hr/>	
Information for Authors . . . . .	1052
<hr/>	
ANNOUNCEMENTS	
Call for Papers—Special Issue of the IEEE TRANSACTIONS ON ELECTRON DEVICES on Silicon Carbide Devices and Technology . . . . .	1053
Call for Papers—Special Issue of the IEEE TRANSACTIONS ON DEVICE AND MATERIALS RELIABILITY on Reliability of GaN, GaAs and Related Compounds . . . . .	1055
Call for Papers—33rd IEEE Photovoltaic Specialists Conference. . . . .	1056
Call for Papers—2008 IEEE EDS Masters Student Fellowship Call for Nomination. . . . .	1057
Call for Papers—2008 International Conference on SISPAD. . . . .	1058

# The Leakage Current of the Schottky Contact on the Mesa Edge of AlGaIn/GaN Heterostructure

Chuan Xu, Jinyan Wang, *Member, IEEE*, Hongwei Chen, Fujun Xu, Zhihua Dong, Yilong Hao, and Cheng P. Wen, *Life Fellow, IEEE*

**Abstract**—A test structure, which is called the ridge-furrow structure, is used to evaluate the leakage current of the Schottky contact on the mesa edge of an AlGaIn/GaN heterostructure. The mesa edge leakage currents were measured at different temperatures from 300 to 500 K and analyzed. The conduction-band-edge energy distribution at the mesa edge is simulated by the Integrated Systems Engineering Technology Computer-Aided Design. Based on the simulation results, the electric field strength can be obtained as a function of reverse bias voltage. The mesa edge leakage current is found to agree with the predicted characteristics, which is based on the Frenkel–Poole emission model. Therefore, we believe that the Frenkel–Poole emission dominates the mesa edge leakage at temperatures between 300 and 500 K.

**Index Terms**—AlGaIn/GaN, characteristic electric field strength, Frenkel–Poole, leakage current, mesa edge, ridge-furrow structure.

## I. INTRODUCTION

AN AlGaIn/GaN heterostructure field-effect transistor (HFET) is attracting much attention as a promising candidate for high-power, high-temperature, high-breakdown, and high-frequency electronic devices, and remarkable achievements were made in the recent years [1]–[4]. However, an excessive leakage current of the reverse-biased Schottky gate contact is identified as a key indicator of poor device reliability. The basic mechanisms of a gate leakage current [5], [6] and a leakage current reduction [5], [7], [8] have been the subjects of several investigations. Tan *et al.* [5] reported that the gate leakage current of a conventional HFET should consist of surface, bulk, and mesa edge leakage components. With the help of a guarded surface leakage test structure, the surface and bulk leakage currents are separated, and the mesa edge leakage can be avoided. Zhang *et al.* [6] analyzed the leakage current mechanisms in the Schottky contacts to both n-GaN and AlGaIn/GaN at different temperatures and concluded that tunneling current dominates at temperature below 150 K, whereas the Frenkel–Poole emission dominates at temperature higher than 250 K. Xiao *et al.* [7] and Shiu *et al.* [8] reported that the AlGaIn/GaN HFETs with implantation isolation

show much reduced gate leakage current than those with mesa etching isolation. However, to date, no attempt has been made to analyze the mesa edge leakage current of an AlGaIn/GaN heterostructure and its mechanism, although similar analysis has been reported in InAlAs/InGaAs heterostructure [9]. In this letter, a test structure called ridge-furrow structure (similar to that in [9]) is used to evaluate the mesa edge leakage current. The results show that the mesa edge leakage current can play an important role in an AlGaIn/GaN HFET. In addition, for the first time, we observe that the mesa edge leakage current obeys the Frenkel–Poole emission law from room temperature to 500 K, similar to the bulk leakage current reported in [6].

## II. EXPERIMENTAL DETAILS

The test structures were fabricated on an unintentionally doped  $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}/\text{GaN}$  (25 nm/2.5  $\mu\text{m}$ ) heterostructure grown by metal–organic chemical vapor deposition on a sapphire substrate (the GaN layer consisted of high-resistivity lower layer 2.3  $\mu\text{m}$  and high-quality upper layer 200 nm). Mesas were formed by using chlorine and inductively coupled plasma (ICP) etching. Sputtered Ti/Al/Ni/Au (20/130/50/150 nm) ohmic contacts were annealed at 900 °C for 30 s. The contact resistance of the ohmic contacts was extracted as 2.1  $\Omega$  mm, and the 2-D electron gas (2DEG) sheet resistance was 453  $\Omega/\text{sq}$ . The Ni/Au (50/100 nm) Schottky contacts were formed by an e-beam evaporation and were annealed at 400 °C for 1 min.

The Schottky metals usually cover the mesa edge sidewalls in order to connect the gate on the surface of an AlGaIn to a pad on the etched surface of a GaN in an HFET device. The objective of the ridge-furrow structure, shown in Fig. 1, is to evaluate the mesa edge leakage current. The 2DEG is grounded by the ohmic contact metals. The measured leakage current contains four components, namely, the bulk AlGaIn leakage current, the bulk GaN leakage current, the mesa edge leakage current, and the surface leakage current. The surface leakage component can be ignored because it is usually several orders lower than the other components if the bias voltage is not too high [5]. Both the bulk AlGaIn leakage current ( $I_{\text{AlGaIn}}$ ) and the bulk GaN leakage current ( $I_{\text{GaN}}$ ) can be estimated from the normal circle dot Schottky contact structure (radius = 40  $\mu\text{m}$ , without mesa edge sidewalls), and we assume that  $I_{\text{AlGaIn}}$  and  $I_{\text{GaN}}$  are area (not perimeter) related. The linear current density of the mesa edge leakage current ( $J_{\Gamma\text{mesa}}$ ) per unit length (in amperes per micrometer) can be expressed as

$$J_{\Gamma\text{mesa}} = (I_{\text{total}} - I_{\text{AlGaIn}} - I_{\text{GaN}})/l_{\text{mesa}} \quad (1)$$

Manuscript received June 20, 2007; revised August 14, 2007. This work was supported by the Engineering Research Institute and National Key Laboratory of Micro/Nano Fabrication Technology, Peking University. The review of this letter was arranged by Editor J. del Alamo.

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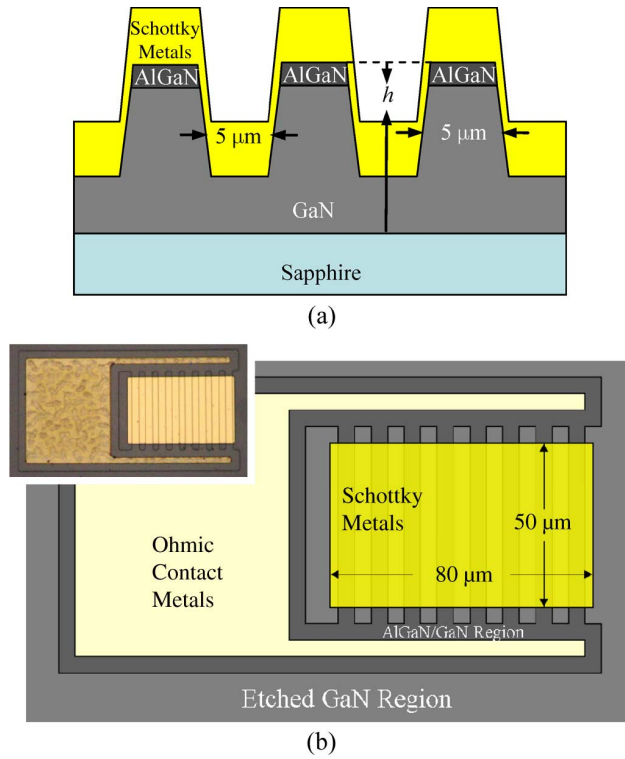


Fig. 1. (a) Cross section and (b) top schematic views of ridge-furrow structure (the inset shows the photograph of the structure).

where  $l_{\text{mesa}}$  is the total edge length of the following structure:

$$l_{\text{mesa}} = 16 \times 50 \mu\text{m}. \quad (2)$$

### III. RESULTS AND DISCUSSION

Fig. 2 shows both the forward and reverse  $I$ - $V$  characteristics of the three components of a ridge-furrow structure shown in Fig. 1. Both  $I_{\text{AlGaN}}$  and  $I_{\text{GaN}}$  were assumed area dominant and extracted from the circle Schottky pads (radius =  $40 \mu\text{m}$ ), whereas  $J_{\Gamma\text{mesa}}$  was extracted by using (1) from the test structure. The leakage current of the Schottky contact on etched surface of a GaN ( $I_{\text{GaN}}$ ) is much smaller than that on an AlGaN ( $I_{\text{AlGaN}}$ ) because the electric field in an AlGaN layer under the Schottky metals is much stronger than that in the high-resistant GaN layer. The mesa edge leakage current ( $J_{\Gamma\text{mesa}}l_{\text{mesa}}$ ) is the major part of the leakage current in the ridge-furrow structure. In comparison with  $I_{\text{AlGaN}}$ ,  $J_{\Gamma\text{mesa}}l_{\text{mesa}}$  does not increase very rapidly as the reverse bias voltage increases due to a smaller increase of the electric field strength at the mesa edge with respect to the absolute value of higher reverse bias voltage.

To analyze the physical mechanism of  $J_{\Gamma\text{mesa}}$ , we first simulated the electrostatic potential distribution, or the conduction band energy distribution at the mesa edge, using the Integrated Systems Engineering Technology Computer-Aided Design (Fig. 3, -1 V reverse bias). The height and the angle of the etching ramp are measured from the scanning electron microscope (SEM) photograph after the ICP etching (before evaporating the Schottky metals), whereas the parameters such as the relative dielectric permittivity, band gap, electron affinity,

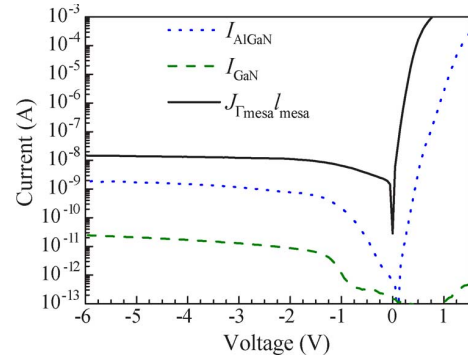


Fig. 2.  $I$ - $V$  characteristics of the three components of a ridge-furrow structure: bulk AlGaN leakage current ( $I_{\text{AlGaN}}$ , dotted line), bulk GaN leakage current ( $I_{\text{GaN}}$ , dashed line), and the mesa edge leakage current ( $J_{\Gamma\text{mesa}}l_{\text{mesa}}$ , solid line).

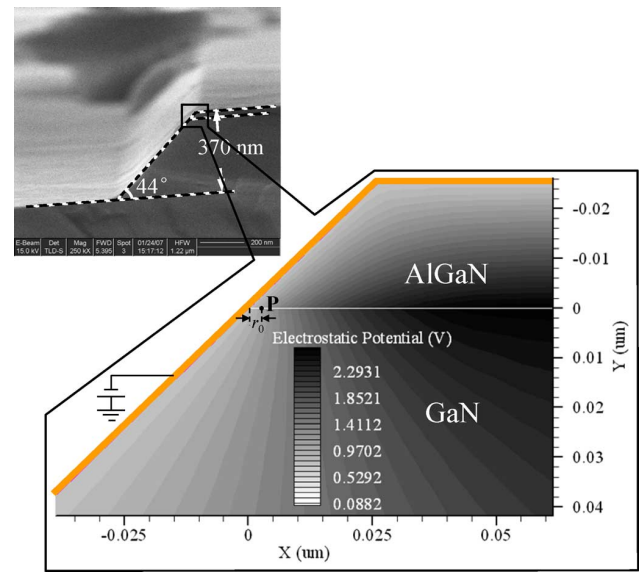


Fig. 3. Electrostatic potential distribution at the mesa edge (reverse bias is -1 V) and the SEM photograph of the etching step (not including the Schottky metals).

and polarization-induced charge could be calculated from the equations in [10] or [11]. The work function of the Schottky metals is defined as 5.0 eV according to [12].

The surface electric field strength is a critical parameter in many compact models of the Schottky leakage current such as the Fowler-Nordheim tunneling and the Frenkel-Poole trap-assisted emission model [5], [6], [13]. However, the electric field strength is a function of position in the area of the mesa edge and reaches the maximum value at the cross line of the mesa edge sidewall and the AlGaN/GaN interface. A characteristic field strength ( $F_c$ ) should be defined for proper application of the leakage current model. The leakage current from the metals to the GaN should dominate because the AlGaN barrier is higher than the GaN barrier. Only the electric field in the GaN is considered in our analysis. We choose the Frenkel-Poole model because the temperature dependency on leakage current is found in our experiment, and also because there are many traps before and after ICP etching [14]. The traps, which are

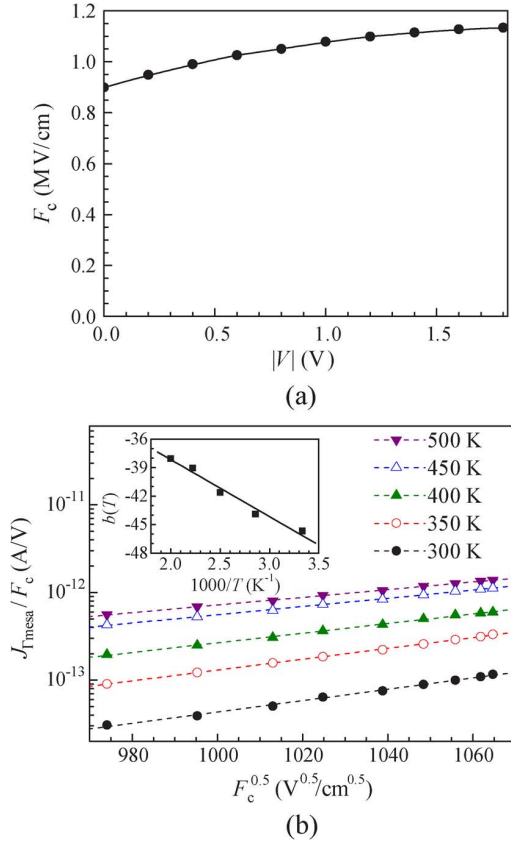


Fig. 4. (a) Characteristic electric field strength  $F_c$  as a function of the reverse bias voltage  $V$  in the case of the Schottky contact on AlGaIn/GaN mesa edge [from simulation results and (3)]. (b) Plot of  $J_{\Gamma\text{mesa}}/F_c$  as a function of  $F_c^{0.5}$  at different temperatures, where  $J_{\Gamma\text{mesa}}$  is the extracted leakage current density at mesa edge [from experimental data and (1)]; the inset shows intercepts  $b(T)$  as a function of  $1000/T$  to obtain  $\varphi_t$ .

very near to the cross line between the mesa edge sidewall and the AlGaIn/GaN interface, should have the greatest effect on the Frenkel–Poole emission. The barrier peak of the electron emitting from such a trap locates at point P (Fig. 3), where both the external electric field strength ( $F_{\text{ext}}$ ) in the GaN side and the trap (positive ion) induced electric field strength ( $F_{\text{ion}}$ ) should be

$$F_{\text{ext}}(\mathbf{P}) = F_{\text{ion}}(\mathbf{P}) = F_c = q/4\pi\epsilon_0\epsilon_s r_0^2 \quad (3)$$

and they should have approximately opposite direction. (According to the simulation,  $F_{\text{ext}}$  in the GaN side at point P has a direction approximately along the AlGaIn/GaN interface.)  $\epsilon_s$  is the relative dielectric permittivity of the GaN at high frequency ( $\epsilon_s = 5.35$  [6]), and  $r_0$  is the distance along the AlGaIn/GaN interface from the metal–semiconductor interface. As shown in Fig. 4,  $F_c$  does not increase very fast as the reverse bias voltage increases.

If the leakage current at the mesa edge ( $J_{\Gamma\text{mesa}}$ ) obeys the Frenkel–Poole emission model [6], it can be expressed as

$$\begin{aligned} J_{\Gamma\text{mesa}} &= CF_c \exp \left[ -q(\varphi_t - \sqrt{qF_c/\pi\epsilon_0\epsilon_s})/kT \right] \\ &\equiv F_c \exp \left( m(T)\sqrt{F_c} + b(T) \right) \end{aligned} \quad (4)$$

where  $\varphi_t$  is the barrier height for electron emitting from the trap state (usually the energy difference between conduction-band-edge and trap state),  $C$  is a constant, and  $m(T)$  and  $b(T)$ , as shown in the following equations, are the slope and intercept of  $\ln(J_{\Gamma\text{mesa}}/F_c) \sim \sqrt{F_c}$  line, respectively:

$$\begin{aligned} m(T) &\equiv \sqrt{q/\pi\epsilon_0\epsilon_s} \cdot q/kT \\ b(T) &\equiv -q\varphi_t/kT + \ln C. \end{aligned} \quad (5)$$

As shown in Fig. 4(b), a linear dependence of  $\ln(J_{\Gamma\text{mesa}}/F_c)$  on  $F_c^{0.5}$  and  $b(T)$  on  $1/T$  are found, which means that the Frenkel–Poole model matches the AlGaIn/GaN mesa edge leakage current. By  $b(T) \sim 1000/T$  plot,  $q\varphi_t$  is extracted as 0.517 eV. Our results show that the mesa edge leakage current at room temperature or higher temperatures has the same mechanism, i.e., the Frenkel–Poole trap-assisted emission, in comparison with the cases of both the Schottky contact on AlGaIn/GaN or bulk GaN [6] and surface leakage current of the Schottky contact on AlGaIn/GaN [5].

#### ACKNOWLEDGMENT

The authors would like to thank Electron Microscope Laboratory, School of Physics, Peking University for their assistance.

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# APPENDIX E



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# APPENDIX G

# The Leakage Current of the Schottky Contact on the Mesa Edge of AlGaIn/GaN Heterostructure

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A test structure, which is called the ridge-furrow structure, is used to evaluate the leakage current of the Schottky contact on the mesa edge of an AlGaIn/GaN heterostructure. The mesa edge leakage currents were measured at different temperatures from 300 to 500 K and analyzed. The conduction-band-edge energy distribution at the mesa edge is simulated by the Integrated Systems Engineering Technology Computer-Aided Design. Based on the simulation results, the electric field strength can be obtained as a function of reverse bias voltage. The mesa edge leakage current is found to agree with the predicted characteristics, which is based on the Frenkel-Poole emission model. Therefore, we believe that the Frenkel-Poole emission dominates the mesa edge leakage at temperatures between 300 and 500 K.

**Published in:** IEEE Electron Device Letters ( Volume: 28 , Issue: 11, November 2007)

**Page(s):** 942 - 944

**INSPEC Accession Number:** 9671410

Date of Publication: 29 October 2007 ?

DOI: 10.1109/LED.2007.906932

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☰ Contents

I. Introduction

An AlGaIn/GaN heterostructure field-effect transistor (HFET) is attracting much attention as a promising candidate for high-power, high-temperature, high-breakdown, and high-frequency electronic devices, and remarkable achievements were made in the recent years [1]–[4]. However, an excessive leakage current of the reverse-biased Schottky gate contact is identified as a key indicator of poor device reliability. The basic mechanisms of a gate leakage current [5], [6] and a leakage current reduction [5], [7], [8] have been the subjects of several investigations. Tan et al. [5] reported that the gate leakage current of a conventional HFET should consist of surface, bulk, and mesa edge leakage components. With the help of a guarded surface leakage test structure, the surface and bulk leakage currents are separated, and the mesa edge leakage can be avoided. Zhang et al. [6] analyzed the leakage current mechanisms in the Schottky contacts to both n-GaN and AlGaIn/GaN at different temperatures. Surface current dominates at temperature below 150 K, whereas the Frenkel–Poole emission dominates at temperature higher than 250 K. Xiao et al. [7] and Shiu et al. [8] reported that the AlGaIn/GaN HFETs with implantation isolation show much reduced gate leakage current than those with mesa etching isolation. However, to date, no attempt has been made to analyze the mesa edge leakage current of an AlGaIn/GaN heterostructure and its mechanism, although similar analysis has been reported in InAlAs/InGaAs heterostructure [9]. In this letter, a test structure called ridge-furrow structure (similar to that in [9]) is used to evaluate the mesa edge leakage current. The results show that the mesa edge leakage current can play an important role in an AlGaIn/GaN HFET. In addition, for the first time, we observe that the mesa edge leakage current obeys the Frenkel–Poole emission law from room temperature to 500 K, similar to the bulk leakage current reported in [6].

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Analogue electronics	695	Nonlinear optics	733
Antennas & propagation	702	Optical communication	734
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Digital electronics	705	Optoelectronics	747
Fibre optics	708	Radiocommunication	752
Image processing	714	Semiconductor technology	753
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#### *Typeset in England by*

Pindar plc

Ryedale Building

First Floor

60 Piccadilly

York YO1 1WU

#### *Printed in UK by*

A.McLay & Co. Limited

Longwood Drive

Forest Farm

Cardiff CF4 7ZB



# Contents

pages 695–774

13th April 2000 Vol. 36 No. 8

<b>ANALOGUE ELECTRONICS</b>	<b>page</b>	<b>INTEGRATED OPTICS</b>	<b>page</b>
<b>Auto-zero differential difference amplifier</b>	695	<b>Self-aligned oxidised porous silicon optical waveguides with reduced loss</b>	722
M. Kayal and Z. Randjelovic ( <i>Switzerland</i> )		N. Vorozov, L. Dolgyi, V. Yakovtseva ( <i>Belarus</i> ),	
<b>Current-reuse bleeding mixer</b>	696	V. Bondarenko, M. Balucani, G. Lamedica,	
S.-G. Lee and J.-K. Choi ( <i>Korea</i> )		A. Ferrari ( <i>Italy</i> ), G. Vitran, J.E. Broquin	
<b>High-speed high-precision min/max circuits in CMOS technology</b>	697	( <i>France</i> ), T.M. Benson, H.F. Arrand	
R.G. Carvajal ( <i>Spain</i> ), J. Ramirez-Angulo		and P. Sewell ( <i>United Kingdom</i> )	
( <i>USA</i> ) and J. Martinez-Heredia ( <i>Spain</i> )			
<b>Phase-locked loop design for on-chip tuning applications</b>	699	<b>LASERS</b>	
J.I. Osa, A. Carlosena and A.J. Lopez-Martin		<b>High temperature (<math>T \geq 425\text{K}</math>) pulsed operation of quantum cascade lasers</b>	723
( <i>Spain</i> )		C. Gmachl, A. Tredicucci, F. Capasso,	
<b>Power consumption modelling of integrated circuit micropower operational amplifiers</b>	701	A.L. Hutchinson, D.L. Sivco, A.M. Sergent,	
J. Stanclik ( <i>Poland</i> )		T. Mentzel and A.Y. Cho ( <i>USA</i> )	
		<b>Low threshold lasing operation of narrow stripe oxide-confined GaInNAs/GaAs multiquantum well lasers at <math>1.28\mu\text{m}</math></b>	725
<b>ANTENNAS &amp; PROPAGATION</b>		S. Illek, A. Ultsch, B. Borchert, A.Y. Egorov	
<b>Switched angular diversity BSSA array antenna for WLAN</b>	702	and H. Riechert ( <i>Germany</i> )	
S. Fassetta and A. Sibille ( <i>France</i> )			
		<b>MICROWAVE TECHNOLOGY</b>	
<b>CIRCUIT THEORY &amp; DESIGN</b>		<b>High-Q frequency-temperature compensated sapphire/rutile resonator</b>	726
<b>Analysis and performance of simple active feedback linearisation scheme</b>	703	J.G. Hartnett, M.E. Tobar, E.N. Ivanov	
T. Nesimoglu, C.N. Canagarajah		( <i>Australia</i> ) and D. Cros ( <i>France</i> )	
and J.P. McGeehan ( <i>United Kingdom</i> )			
		<b>MODULATION &amp; CODING</b>	
<b>DIGITAL ELECTRONICS</b>		<b>Code for spectral amplitude coding optical CDMA systems</b>	728
<b>Dual TLB structure for supporting two page sizes</b>	705	Xiang Zhou, H.H.M. Shalaby, Chao Lu	
Jung-Hoon Lee, Jang-Soo Lee, Gi-Ho Park,		and Teehiang Cheng ( <i>Singapore</i> )	
Kil-Whan Lee and Shin-Dug Kim ( <i>Korea</i> )		<b>Improved performance analysis of spiral curve-phase precoding</b>	729
<b>Ultra-low-voltage bootstrapped CMOS driver for high performance applications</b>	706	K. Sripimanwat, R.M.A.P. Rajatheva	
Kiat-Seng Yeo, Jian-Guo Ma and Manh-Anh Do		and K.M. Ahmed ( <i>Thailand</i> )	
( <i>Singapore</i> )		<b>Iterative PDF estimation and decoding for CDMA systems with non-Gaussian characterisation</b>	730
		Yuan Li and Kwok H. Li ( <i>Singapore</i> )	
<b>FIBRE OPTICS</b>		<b>Performance of bit-interleaved turbo-coded modulations on Rayleigh fading channels</b>	731
<b>Absolute strain measurement using an in-fibre-Bragg-grating-based Fabry-Perot sensor</b>	708	S. Le Goff ( <i>United Arab Emirates</i> )	
Y.J. Rao ( <i>China</i> ), M.R. Cooper, D.A. Jackson,			
C.N. Pannell and L. Reekie ( <i>United Kingdom</i> )		<b>NONLINEAR OPTICS</b>	
<b>Broadband four-wave mixing generation in short optical fibres</b>	709	<b>Second-order nonlinear susceptibility in <math>\text{As}_2\text{S}_3</math> chalcogenide thin glass films</b>	733
O. Aso, Shin-ichi Arai, T. Yagi, M. Tadakuma,		Y. Quiquempois, A. Villeneuve, D. Dam,	
Y. Suzuki and S. Namiki ( <i>Japan</i> )		K. Turcotte, ( <i>Canada</i> ), J. Maier, G. Stegeman	
<b>Efficient cladding-pumped Tm-doped silica fibre laser with high power singlemode output at <math>2\mu\text{m}</math></b>	711	( <i>USA</i> ) and S. Lacroix ( <i>Canada</i> )	
R.A. Hayward, W.A. Clarkson, P.W. Turner,			
J. Nilsson, A.B. Grudinin and D.C. Hanna		<b>OPTICAL COMMUNICATION</b>	
( <i>United Kingdom</i> )		<b><math>4 \times 40\text{Gbit/s}</math> RZ ETDM transmission over 520km of NDSF at 120 and 160km span lengths with Raman pre-amplification</b>	734
<b>Long-distance transmission of bandwidth-managed solitons in fibres with alternating dispersion</b>	713	W.S. Lee, B. Patel, Y.J. Zhu, C. Scahill,	
V.S. Grigoryan ( <i>USA</i> )		D. Watley, M. Jones, G. Pettitt, C. Fludger,	
		B. Shaw, A. Hadjifotiou ( <i>United Kingdom</i> )	
<b>IMAGE PROCESSING</b>		and D. Way ( <i>USA</i> )	
<b>Calculation of 3D trajectories of moving objects from unsynchronised stereo video signals</b>	714	<b>Excess penalty impairments of polarisation shift keying transmission format in presence of polarisation mode dispersion</b>	736
Hyunwoo Kim, Yongduek Seo		J.J. Lepley, J.G. Ellison, S.G. Edirisinghe,	
and Ki Sang Hong ( <i>Korea</i> )		A.S. Siddiqui and S.D. Walker	
<b>Fractal image compression with simple classification scheme in frequency domain</b>	716	( <i>United Kingdom</i> )	
J.H. Jeng and J.R. Shyu ( <i>China</i> )		<b>Measurement of 200Gbit/s optical eye diagram by optical sampling with gain-switched optical pulse</b>	737
<b>Morphological smoothing</b>	717	H. Ohta, S. Nogiwa, Y. Kawaguchi	
Woonkyung M. Kim, S. Moon-Ho Song,		and Y. Endo ( <i>Japan</i> )	
Sun Geun Kim, Chuck Yoo, Chongyul Yoon		<b>Spectral hole burning effects on partially loaded, 19nm bandwidth, 6246km long EDFA lightwave transmission system</b>	739
and Jung Soo Kim ( <i>Korea</i> )		F.I. Khatri, D.G. Duff, M. Vaa and A.L. Simons	
<b>Robust multi-view correspondence of noisy 2D points using relaxation</b>	719	( <i>USA</i> )	
Dong Hoon Lee, Soon Ki Jung and			
Kwangyun Wohn ( <i>Korea</i> )			
<b>Shadow generation from stereo images</b>	720		
Jen-Hui Chuang, Lou-Wei Kuo, Hao-Jui Kuo			
and Jain-Shing Liu ( <i>China</i> )			

(continued overleaf)



# Contents

## OPTICAL DEVICES & MATERIALS

<b>High performance optical receiver module for 10Gbit/s applications with low cost potential</b>	<b>741</b>
A. Ebberg (Germany), R. Bauknecht (Switzerland), M. Bittner, M. Grumm (Germany) and M. Bitter (Switzerland)	
<b>Long-period fibre gratings written by CO<sub>2</sub> exposure of H<sub>2</sub>-loaded, standard fibres</b>	<b>742</b>
L. Drozin, P.-Y. Fonjallaz and L. Stensland (Sweden)	
<b>Vectorial model of Bragg gratings</b>	<b>744</b>
L. Berthelot, J. Gourhant, I. Riant and P. Sansonetti (France)	
<b>Wavelength-selectable microarray light sources of multiple ranges simultaneously fabricated on single wafer</b>	<b>745</b>
K. Kudo, T. Morimoto, K. Yashiki, T. Sasaki, Y. Yokoyama, K. Hamamoto and M. Yamaguchi (Japan)	

## OPTOELECTRONICS

<b>60GHz high output power uni-travelling-carrier photodiodes with integrated bias circuit</b>	<b>747</b>
H. Ito, T. Ohno, H. Fishimi, T. Furuta, S. Kodama and T. Ishibashi (Japan)	
<b>GaAs/AlGaAs waveguide pin photodiodes with non-absorbing input facets fabricated by quantum well intermixing</b>	<b>749</b>
S.D. McDougall, M.J. Jubber, O.P. Kowalski, J.H. Marsh and J.S. Aitchison (United Kingdom)	
<b>RF saturation mechanism of InP/InGaAs uni-travelling-carrier photodiode</b>	<b>750</b>
N. Shimizu, Y. Miyamoto, A. Hirano, K. Sato and T. Ishibashi (Japan)	

## RADIOCOMMUNICATION

<b>Performance of MC-CDMA system using controlled MRC with power control in Rayleigh fading channel</b>	<b>752</b>
Yu Zhu and E. Gunawan (Singapore)	

## SEMICONDUCTOR TECHNOLOGY

<b>Enhancement mode AlGaIn/GaN HFET with selectively grown pn junction gate</b>	<b>753</b>
X. Hu, G. Simin, J. Yang and M. Asif Khan, R. Gaska and M.S. Shur (USA)	
<b>Laser processing for enhanced performance thin film electroluminescent devices</b>	<b>754</b>
W.M. Cranton, E.A. Mastio, C.B. Thomas, C. Tsakonas and R. Stevens (United Kingdom)	

<b>Low contact resistance of poly-plug structure by in-situ HF-vapour cleaning</b>	<b>756</b>
--	------------

Jiann Heng Chen, Tan Fu Lei, Tien Sheng Chao, Tien Pao Su, J. Huang, A. Tuan and S.K. Chen (China)

<b>Transient processes in AlGaIn/GaN heterostructure field effect transistors</b>	<b>757</b>
---	------------

S.L. Rumyantsev, M.S. Shur, R. Gaska, X. Hu, A. Khan, G. Simin, J. Yang, N. Zhang, S. DenBaars and U.K. Mishra (USA)

## SIGNAL PROCESSING

<b>Adaptive algorithm for direct estimation of sinusoidal frequency</b>	<b>759</b>
H.C. So (Hong Kong)	
<b>Combinatorial approach to representing subsets of coefficients for signal compression schemes</b>	<b>760</b>
D.C. Popescu and D. Bone (Australia)	
<b>Superposition of multiplicative multifractal traffic processes</b>	<b>761</b>
J. Gao and I. Rubin (USA)	
<b>Time-varying filtering of speech signals using linear prediction</b>	<b>763</b>
S. Stanković and J. Tilp (Germany)	

## SYSTEMS & CONTROL ENGINEERING

<b>Control strategy for power smoothing using vector controlled induction machine and flywheel</b>	<b>765</b>
R. Cárdenas, R. Peña (Chile) and J. Clare (United Kingdom)	
<b>Efficient acceleration and deceleration technique for short distance movement in industrial robots and CNC machine tools</b>	<b>766</b>
Jae Wook Jeon (Korea)	
<b>Large scale interval system modelling using Routh approximants</b>	<b>768</b>
G.V.K.R. Sastry, G. Raja Rao and P. Mallikarjuna Rao (India)	
<b>Pertinent parameters for Kautz approximation</b>	<b>769</b>
R. Morvan, N. Tanguy, P. Vilbé and L.C. Calvez (France)	
<b>Railway junction conflict resolution by genetic algorithm</b>	<b>771</b>
T.K. Ho and T.H. Yeung (Hong Kong)	

## TELECOMMUNICATION

<b>Efficient algorithm for achieving GWPMM fairness in ATM ABR services</b>	<b>772</b>
Yihong Long (China) and T.K. Ho (Hong Kong)	
<b>Errata</b>	<b>774</b>

$$TLR = \frac{\frac{1}{2}\rho_{thresh}^2}{P_{local}} \quad (1)$$

The value of TLR must be chosen such that it minimises the BER.

**Simulation results:** In the simulation, the spreading gain  $N$  was set to 128. The spreading code was chosen to be a Walsh-Hadamard code with length 128. All the users were assumed to suffer from independent Rayleigh fading. It was also assumed that the fading were independent among the different subcarriers. The signal to noise ratio (SNR) was defined throughout the simulation as  $SNR = P_{local}/\sigma_n^2$ , where  $\sigma_n^2$  is the additive white Gaussian noise (AWGN) noise power.

Fig. 3 shows the optimal value of TLR required to minimise the BER performance of a 10-user system at a particular SNR value. As expected, the optimal TLR value decreases while the SNR increases. If we consider the situation where the signal power  $P_{local}$  is constant, the TLR should be higher, when the SNR is small, to effectively eliminate deep fading or noise contaminated subcarriers. On the other hand, when the SNR is large, the optimal value of TLR will be small since the noise or fading level is not high. It is observed that the optimal TLR changes from  $\sim 0.3$  to  $-0.5$  dB as the SNR varies from 1 to 15 dB.

A BER performance comparison is shown in Fig. 4. It is obvious that the suggested controlled MRC algorithm with power control outperforms the MRC algorithm. Here the optimal threshold was used in the simulation for the controlled MRC with power control algorithm. The improvement is about five users for  $BER = 10^{-3}$ . However, for larger SNR values, the improvement is not as high. This can be explained as follows. When the noise level is low or no deep fading signal is present, then few or no subcarriers will be cut off, therefore the difference between controlled MRC and MRC will be insignificant.

**Conclusion:** A controlled MRC algorithm has been proposed for an MC-CDMA uplink system under Rayleigh fading channel and AWGN conditions. The optimal threshold value for such an algorithm has been obtained by simulation for various SNR values. It has been shown that the controlled MRC algorithm can improve the MC-CDMA uplink performance, especially in low SNR environments. However, when the SNR is high, the proposed method does not lead to noticeable improvements.

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15 February 2000

Electronics Letters Online No: 20000549

DOI: 10.1049/el:20000549

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## Enhancement mode AlGaIn/GaN HFET with selectively grown $pn$ junction gate

X. Hu, G. Simin, J. Yang, M. Asif Khan, R. Gaska and M.S. Shur

A report is presented into the fabrication and characterisation of an enhancement mode AlGaIn/GaN heterojunction field-effect transistor (HFET) with selectively grown  $pn$  junction gate. At zero gate bias the device channel is depleted due to the high built-in potential of the gate-channel junction. The selective area growth approach enables both depletion and enhancement mode HFETs to be fabricated on the same wafer thus opening up the possibility of designing high speed, low consumption GaN-based logical integrated circuits.

Since the first demonstration of a depletion mode AlGaIn/GaN high electron mobility transistor (HEMT) [1], there has been rapid progress towards the realisation of high power microwave devices [2, 3]. However to date few reports have been made of AlGaIn/GaN based enhancement mode transistors. Khan *et al.* reported such a device using AlGaIn/GaN heterojunctions where a Schottky barrier gate was used [4]. For high temperature digital IC applications it is ideal to fabricate both enhancement and depletion mode (AlGaIn/GaN) devices in selective areas on the same wafer. In this Letter we describe a novel approach to realising an enhancement mode AlGaIn/GaN heterostructure field effect transistor (HFET) with a selective area grown  $pn$  junction gate. The  $p$ -GaIn layers for the gate were grown in selective areas defined by openings in an  $SiO_2$  mask. Our novel approach therefore opens up the possibility of monolithically integrating AlGaIn/GaN based normally-on and normally-off logic devices on a single wafer.

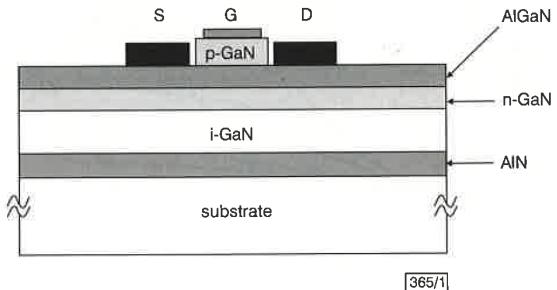


Fig. 1 Schematic diagram of structure of  $pn$  junction regrown gate HFET

The epilayer structure for our devices is schematically shown in Fig. 1. It was deposited over a basal plane sapphire substrate using low pressure metal organic chemical vapour deposition (MOCVD) epitaxy. The 300 Å AlN buffer layer of our structure was deposited at 400°C and 76 torr. All the other layers were deposited at 1000°C and 76 torr. The  $Al_{0.2}Ga_{0.8}N$  barrier layer was 300 Å thick and was silicon-doped to  $n = 3 \times 10^{18} \text{ cm}^{-3}$ . All layers of the structure were grown with a low-level flux of trimethylindium (TMI). This incorporates trace amount of In in all the layers and helps with the layer and interface smoothness. For the structure, the room temperature sheet carrier density and mobility were measured to be  $n_s = 8 \times 10^{12} \text{ cm}^{-2}$  and  $\mu = 1000 \text{ cm}^2/\text{V.s}$ .

Mg-doped 1000 Å thick  $p$ -GaIn ( $p = 10^{17} \text{ cm}^{-3}$ ) was then selectively grown using  $10 \mu\text{m} \times 150 \mu\text{m}$  openings in a 1000 Å thick  $SiO_2$  masking layer. The  $SiO_2$  mask layer was deposited using a plasma enhanced chemical vapour deposition (PECVD) system. Transistors were then fabricated with Ti/Al/Ti/Au (100 Å/200 Å/100 Å/500 Å) source-drain contacts. The contacts were then RTA annealed at 850°C for 1 min in a nitrogen ambient. Ni/Au contacts were then deposited over the selective area grown  $p$ -GaIn regions. These were annealed at 450°C in oxygen ambient. Our transistor structure thus had a gate length of  $10 \mu\text{m}$  and a gate width of  $150 \mu\text{m}$ . The source drain opening was  $10 \mu\text{m}$ . Note that this geometry was selected only for a proof of principle. For higher performance devices much shorter gate lengths and source drain distances will be required.

In Fig. 2a we include the source drain current-voltage characteristics. As seen at zero gate bias the device does not conduct because the channel is depleted due to the high built-in voltage of the  $pn$  junction gate. With positive gate voltage the device reaches a saturation current of 40 mA/mm at +4 V gate bias. Fig. 2b shows the external transconductance  $g_m$  as a function of gate bias measured at 25 V drain to source voltage. The peak  $g_m$  value of 10 mS/mm is reached at +3 V gate bias. These  $I_{ds}$  and  $g_m$  values are limited by the low channel conductance from the very large gate and channel length ( $10 \mu\text{m}$ ). Assuming an inverse linear dependence of both saturation current and transconductance on the gate length, we estimate these values to be 400 mA/mm and 150 mS/mm, respectively, for a  $1 \mu\text{m}$ -gate device. These estimated values of  $I_{ds}$  and  $g_m$  are quite close to those typically reported for depletion mode devices.

The maximum current for heterostructure field-effect transistors depends on the maximum charge induced in the device channel.



This charge increases with the increase in positive gate bias (for an  $n$ -channel device). Thus the maximum saturation current is limited by the gate leakage at positive bias. For our enhancement mode transistor with a  $pn$  junction gate, the range of positive gate bias which maintains a low gate leakage current is significantly larger than that for a regular Schottky-gate device. This is illustrated by Fig. 3 showing gate channel I-V curves for a  $pn$  junction gate enhancement mode HFET and a regular Schottky gate HFET on the same wafer. As seen, for a  $pn$  junction gate device the maximum operating gate voltage can be as high as 3V as compared to ~1V maximum operating voltage for a Schottky gate HFET. This proves that in principle,  $pn$  junction gate enhancement mode HFETs can provide much higher induced channel charge, and hence, saturation current and transconductance as compared to a Schottky gate depletion mode HFET.

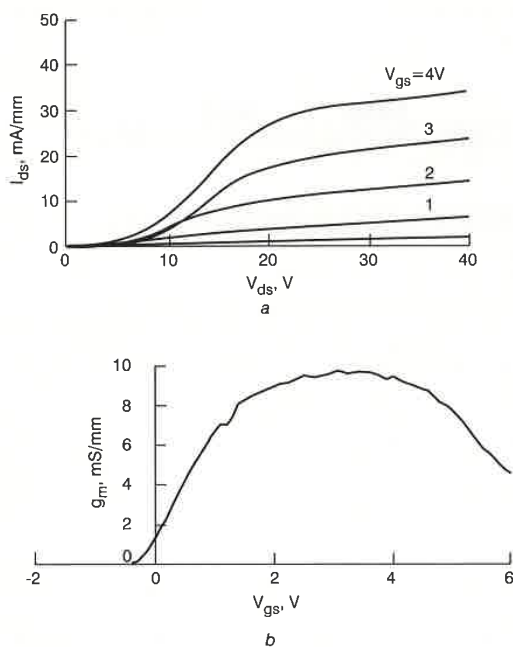


Fig. 2 Current-voltage characteristics of enhancement mode  $pn$  junction gate HFET

a Channel current dependence on drain to source voltage  
b Transconductance dependence on gate bias

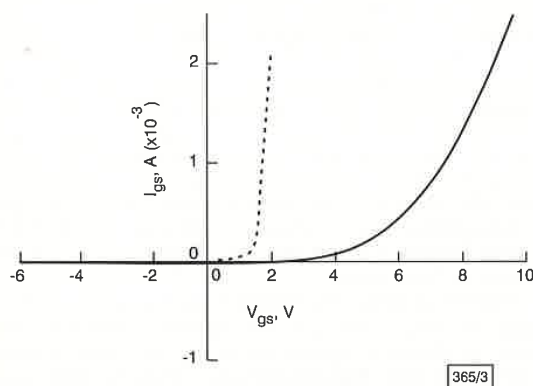


Fig. 3 Current voltage characteristics of  $pn$  junction and Schottky gate devices

—  $pn$  junction device  
--- Schottky gate device

Our estimates of the threshold voltage as a function of the distance between the channel and the gate showed that the effective channel-to-gate separation is close to the thickness of the AlGaIn layer. This means that the  $p$ -type AlGaIn layer operates as a  $p$ -type gate. As a result, the threshold voltage is shifted by ~2.5V towards positive values (i.e. by the difference between the GaN energy gap and the Schottky barrier height).

In Fig. 3 it can be seen that the differential resistance of the  $pn$  junction gate is ~1k $\Omega$ . This resistance is largely due to the relatively low doping level in regrown  $p$ -material as well as to the low hole mobility in  $p$ -GaN. The  $pn$  junction gate capacitance was measured to be < 1pF. Using these values of gate series resistance and capacitance, we estimate the characteristic time constant RC of our enhancement mode HFET to be < 1ns. By making use of a higher doping level in the  $p$ -GaN gate material and with shorter gate length this time constant can be considerably decreased to achieve switching rates in the gigabit per second range.

In conclusion we have fabricated a new enhancement mode GaN/AlGaIn HEMT with a selective area deposited  $pn$  junction gate. We have also established the feasibility of our approach to produce enhancement and depletion mode GaN/AlGaIn HEMTs on the same wafer. This is an important step towards the goal of realising monolithically integrated logic circuits based on AlGaIn/GaN heterojunctions.

**Acknowledgment:** This work was supported by the Ballistic Missile Defense Organization (BMDO) under Army SSDC contract DASG60-97-C 0066, monitored by B. Strickland and K. Wu. The work at RPI was partially supported by the Office of Naval Research (Program monitor J. Zolper).

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Electronics Letters Online No: 20000557

DOI: 10.1049/el:20000557

21 February 2000

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## Laser processing for enhanced performance thin film electroluminescent devices

W.M. Cranton, E.A. Mastio, C.B. Thomas, C. Tsakonas and R. Stevens

A technique for enhancing the performance of thin film electroluminescent devices is presented. Thin film phosphors have been processed with 20ns pulses of 880mJ/cm<sup>2</sup> laser irradiation from a 249nm KrF excimer laser. Electroluminescent characterisation demonstrates a four-fold improvement in emitted luminous intensity, as compared to thermally annealed structures.

**Introduction:** Thin film electroluminescent (TFEL) devices utilising ZnS:Mn phosphor films are important in the field of large area flat panel displays. These displays have benefits such as ruggedness, low power, high contrast, full colour capability, high temperature operating range, and large viewing angle [1]. They are suitable for both text and graphics based systems and, as demonstrated by the Displays Group at Nottingham Trent University

# APPENDIX I

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035 ##$a(Horizon)723151
035 ##$a(MoKL)513799-1halldb
035 ##$a(1halldb)513799-1halldb
037 ##$bPublication Sales Dept., IEE, Station House, Nightengale Rd., Hitchin, Herts., SG5 1RJ, England
040 ##$aMUL $cMUL $dCOO $dOCL $dDLC $dNSD $dSER $dAIP $dNST $dOCL $dMYG $dCUS $dMYG $dSYS $dIEEEX $dOCLCQ $dNLM $dOCLCQ $dLVB $dMYG $beng
042 ##$alc $ansdp
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210 0# $aElectron. lett.
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246 14$aIEE electronics letters $f<Aug. 2006>-Dec. 2006
246 14$aIET electronics letters $fJan. 2007-
260 ##$aStevenage, UK : $bInstitution of Electrical Engineers
300 ##$av. : $bill. ; $c30 cm.
310 ##$aBiweekly (except 1 issue in Dec.) $b<, 29 Apr. 1982- >
321 ##$aBiweekly $b<, May 1976- >
321 ##$aMonthly, $b1965-
362 1# $aBegan with: Vol. 1 (Mar. 1965).
500 ##$aPublished: Institution of Engineering and Technology, 2007-
500 ##$aDescription based on: Vol. 42, no. 17 (Aug. 17th, 2006).
500 ##$aLatest issue consulted: Vol. 43, no. 1 (Jan. 4th, 2007).
500 ##$aV. 25 includes a special issue.
510 2# $aChemical abstracts $x0009-2258
530 ##$aAvailable in microfiche.
555 ##$aVols. 1-7, 1965-71. 1 v.
590 ##$aSelected volumes/issues gifts of the American Institute of Aeronautics and Astronautics.
650 #0$aElectronics $vPeriodicals
710 2# $aInstitution of Electrical Engineers
710 2# $aInstitution of Engineering and Technology
850 ##$aDGW $aDLC $aICU $aIaU $aMBU $aMnU $aNN $aNSyU $aNjP $aNjR $aULA
891 33$9853 $81 $av. $bno. $uvar $vr $i(year) $j(month) $wx $x01
891 40$9863 $81 $a<16>- $i<1980>- $xprovisional
936 ##$aAACR2=MYG
948 ##$aLTI 09/01/2008
948 ##$aLTI 04/27/2010
948 ##$aLTI 10/19/2010
994 ##$aC0 $bLHL

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# APPENDIX J

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Title	Electronics letters
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## Electronics letters

IEE electronics letters <Aug. 2006>-Dec. 2006

IET electronics letters Jan. 2007-

**Creator/Contributor** Institution of Electrical Engineers >

Institution of Engineering and Technology &gt;

Subjects Electronics >

Identifier ISSN : 0013-5194

OCLC : (OCoLC)1567764

**Publisher** Stevenage, UK : Institution of Electrical Engineers

Began with: Vol. 1 (Mar. 1965).

Creation date	1965
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**Format** v. : ill. ; 30 cm.

**Frequency** Biweekly (except 1 issue in Dec.) <, 29 Apr. 1982- >

**General notes** Published: Institution of Engineering and Technology, 2007-

Description based on: Vol. 42, no. 17 (Aug. 17th, 2006).

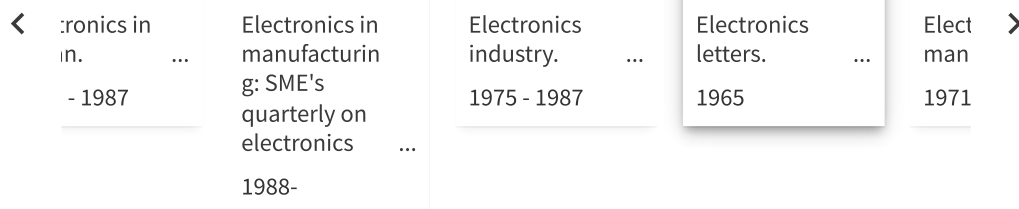
Latest issue consulted: Vol. 43, no. 1 (Jan. 4th, 2007).

V. 25 includes a special issue.

**Citation/References**      Chemical abstracts  
**note**

<b>Local notes</b>	Selected volumes/issues gifts of the American Institute of Aeronautics and Astronautics.
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v.36(2000)-v.46(2010)

v.47:no.1(2011:Jan.6)-v.47:no.10(2011:May 12),v.47:no.13(2011:Jun.23)-v.49:no.25(2013:Dec.5)-

**Supplementary Material:**

Special Supplement: Silicon photonics (June 2009)

Special Supplement: Terahertz Technology (December 2010)

2011:Dec. "Semiconductors in Personalised Medicine"

**Indexes:**

Vol. 35-37 (1999)

Vol. 38 (2002)

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Annual indexes received separately.

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