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VLSI TECHNOLOGY

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Bell Laboratories, Incorporated

Murray Hill, New Jersey

McGraw-Hill Book Company

New York St. Louis San Francisco Auckland Bogotá Hamburg
Johannesburg London Madrid Mexico Montreal New Delhi
Panama Paris São Paulo Singapore Sydney Tokyo Toronto

SONY 1031

This book was set in Times Roman by Information Sciences Corporation.
The editors were T. Michael Slaughter and Madelaine Eichberg;
the production supervisor was Leroy A. Young.
The cover was designed by Joseph Gillians.
The drawings were done by Bell Laboratories, Incorporated.
Halliday Lithograph Corporation was printer and binder.

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34567890HALHAL8987654

ISBN 0-07-062686-3

Library of Congress Cataloging in Publication Data
Main entry under title:

VLSI technology.

(McGraw-Hill series in electrical engineering.
Electronics and electronic circuits)

Includes index.

I. Integrated circuits—Very large scale
integration. I. Sze, S. M., date

II. Series.

TK7874.V566 1983 621.381'73 82-24947

ISBN 0-07-062686-3

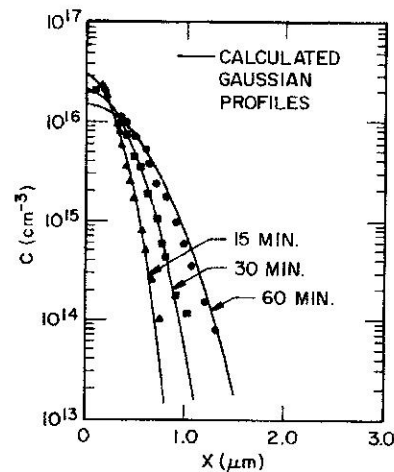


Fig. 6 Phosphorus profiles from C-V measurement. Phosphorus implantation: ion energy = 30 keV, ion dose = 10^{12} cm^{-2} . Diffusion at 1100°C in oxygen. Calculation $2Dt = 1.7 \times 10^{-9} \text{ cm}^2$, $\Delta R_p^2 = 1.7 \times 10^{-12} \text{ cm}^2$, $S = 8 \times 10^{11} \text{ cm}^{-2}$, $D = 2.3 \times 10^{-13} \text{ cm}^2/\text{s}$.

$S = 8 \times 10^{11} \text{ cm}^{-2}$ which is within 20% of the implant dose. The ΔR_p^2 is one-thousandth of $2Dt$; thus the implanted profile can be assumed to be a delta function (i.e., all the implanted atoms are confined to a very thin sheet with a total phosphorus concentration S and less than 20% of the implant dose is incorporated into the oxide film which was grown during the diffusion).

Differential conductivity technique Differential conductivity is one of the oldest techniques for measuring the diffusion profiles in silicon by the electrical method.²⁷ This technique involves repeatedly measuring the sheet resistance of a diffused layer by the four-point probe measurement after removing a thin layer of silicon by anodic oxidation and etching the oxide off in HF solution. Because the anodic oxidation is at room temperature, the impurity atoms do not move in the diffused layer during oxidation and there is no segregation effect; hence, a true distribution profile can be determined. To use this technique, either the carrier mobility is measured by the Hall effect measurement or the resistivity versus impurity concentration curves are used.²⁸ Figure 23 of Chapter 1 gives the composite curves of the resistivities for boron- and phosphorus-doped silicon over a wide range of concentrations. The polynomial fittings for calculating the impurity concentration from resistivity measurements are given in Ref. 28. The differential conductivity technique is not suitable for diffusion study in VLSI process development.

Spreading resistance technique The C-V technique has a limited range of junction depths and dopant concentration that can be used for profile measurement, and the differential-conductivity technique is a time-consuming method for profiling diffused layers. Various techniques have been investigated to improve the spatial resolution and to reduce the measurement time, and as a result, the two-point probe spreading

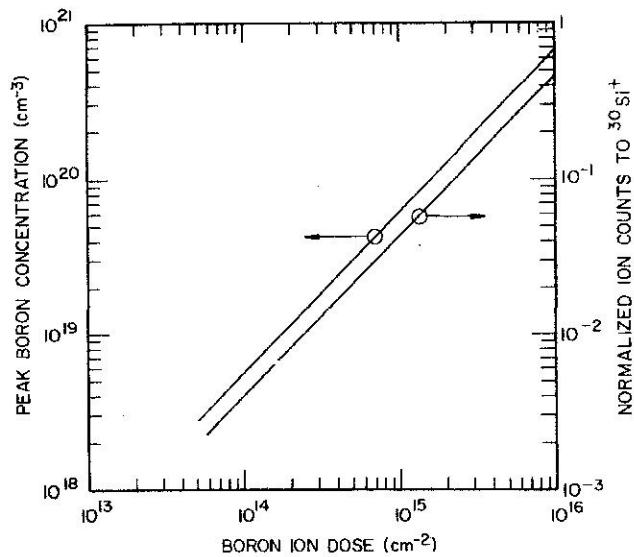


Fig. 8 SIMS analysis calibration curves. Peak boron concentration versus boron ion dose and normalized peak ion counts to ^{30}Si ion counts versus boron ion dose.

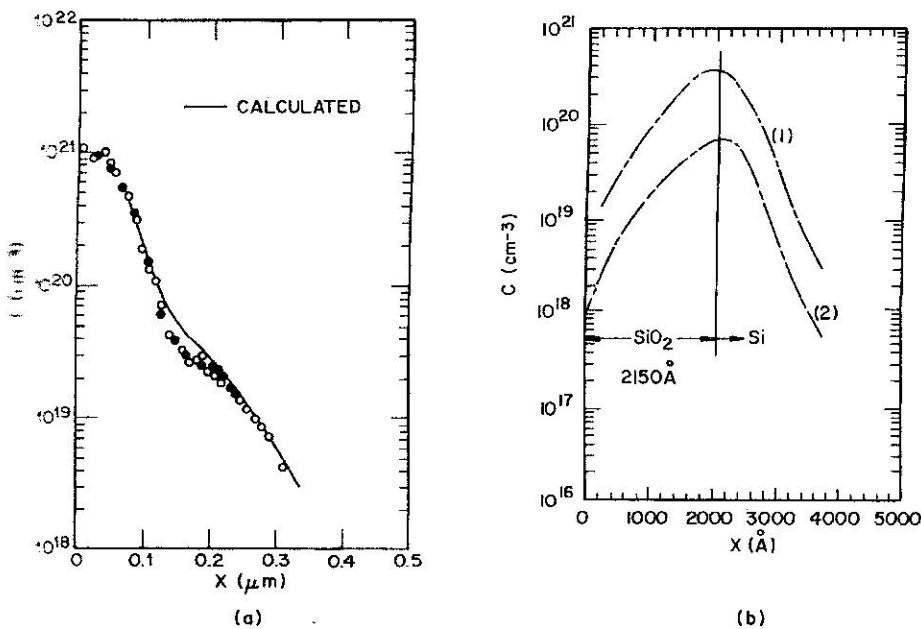


Fig. 9 Examples of SIMS profiles. (a) Phosphorus diffusion profile in silicon. Diffusion at 900°C for 30 min. POCl_3 source. \circ Differential conductivity data. \bullet SIMS data. (After Fair, Ref. 21.) (b) Boron implanted profile in SiO_2 and Si. (1) Ion dose = $5 \times 10^{15} \text{ cm}^{-2}$, (2) Ion dose = $1 \times 10^{15} \text{ cm}^{-2}$. Implant energy = 50 keV.

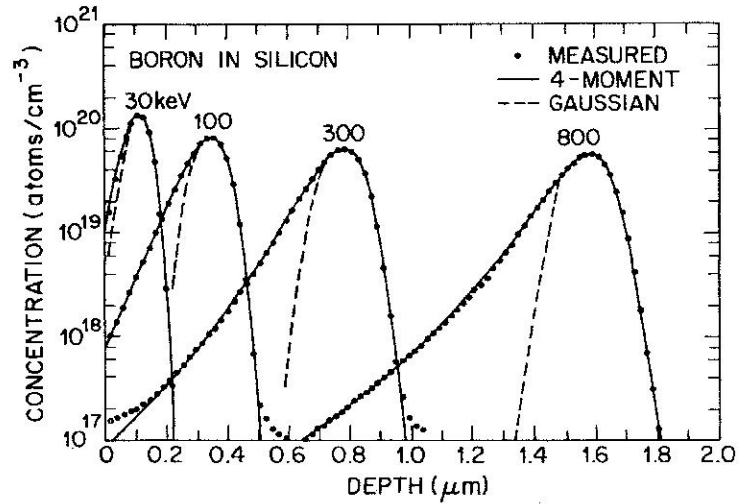


Fig. 5 Boron implanted atom distributions, with measured data points, and four-moment (Pearson-IV) and symmetric Gaussian curves. The boron was implanted into amorphous silicon without annealing. (After Hofker, Ref. 21.)

Figure 6a shows a "thick" ion mask (thickness $\gg R_p + \Delta R_p$) with a vertical-slotted window. In this figure the slot's long direction (z) is into the paper, the short direction (y) has a slot width of $2a$, and x is the depth coordinate. The profile is given by

$$n(x, y) = \frac{n(x)}{2} \left[\operatorname{erfc} \left[\frac{y-a}{\sqrt{2} \Delta R_1} \right] - \operatorname{erfc} \left[\frac{y+a}{\sqrt{2} \Delta R_1} \right] \right] \quad (9)$$

where $n(x)$ is the depth distribution density far away from the mask edge. For $a \gg \Delta R_1$, $n(x, a) \equiv n(x)/2$, which is the result²² expected for a "half-source." Figure 6a is for $a \gg \Delta R_1$, the edges are far removed from each other. Figure 6b shows the contours of equal-ion concentration for 70-keV boron into a 1- μm slit. The lateral doping extends well under the mask edge and will effect the channel length of a short gate.

6.3.2 Theory of Ion Stopping

The range of an ion is determined by Lindhard, Scharff, and Schiott (LSS) theory,¹ where energy loss mechanisms are considered to be independent of each other and additive. For electronic and nuclear stopping, the energy loss per unit length is defined as

$$\left| \frac{dE}{dx} \right|_{\text{total}} = \left| \frac{dE}{dx} \right|_{\text{nuclear}} + \left| \frac{dE}{dx} \right|_{\text{electronic}} \quad (10)$$

The nuclear and electronic energy loss, are both functions of energy.

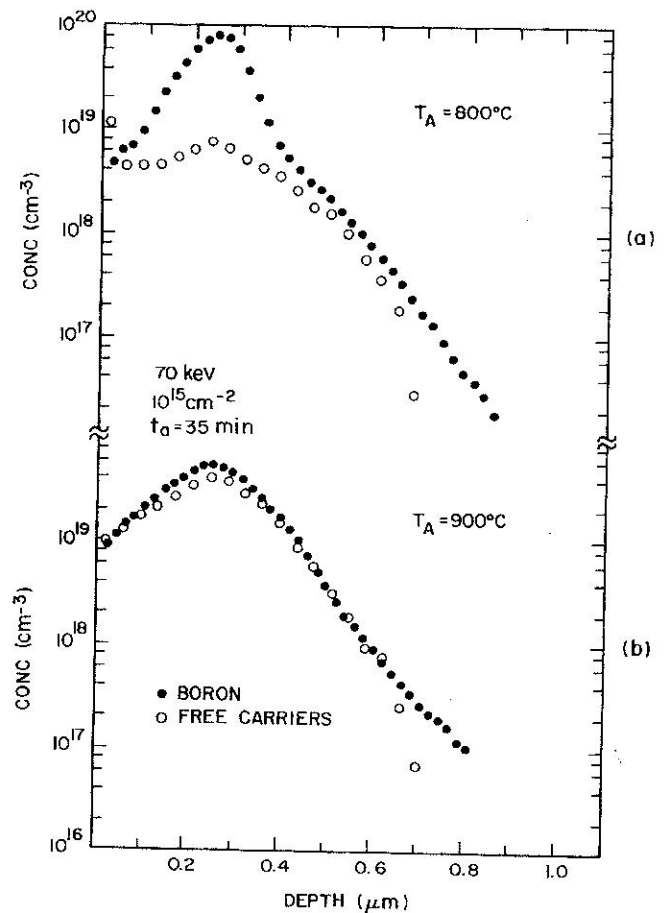


Fig. 19 Concentration profiles of boron atoms (SIMS—solid dots) and corresponding free-carrier concentrations (Hall data—open circles). (a) At 800°C and (b) at 900°C. (After Hofker, Ref. 21.)

$\langle 111 \rangle$ orientation at 550°C (Fig. 20). For the $\langle 111 \rangle$ surface, the slower rate is accompanied by defective (twinned) silicon. This is proposed to be due to growth along inclined (111) planes.

Plotting the regrowth rates against reciprocal temperature gives an activation energy of 2.3 eV. This low temperature process is associated with bond breaking to allow reordering at the interface. Adding impurities such as O, C, N, or Ar slows or disorganizes the regrowth, presumably because the impurities tie up (remove) broken bonds. Impurities such as B, P, or As increase the growth rate (by a factor of about 2 for 10²⁰ impurity atoms/cm³) because the substitutional impurities weaken and increase the likelihood of having broken bonds.

For certain cases (such as high-dose arsenic), annealing at temperatures near 550°C followed by a high temperature results in a more orderly recrystallization process.⁴⁷ If the formation of polycrystals or high-concentration dislocations can be

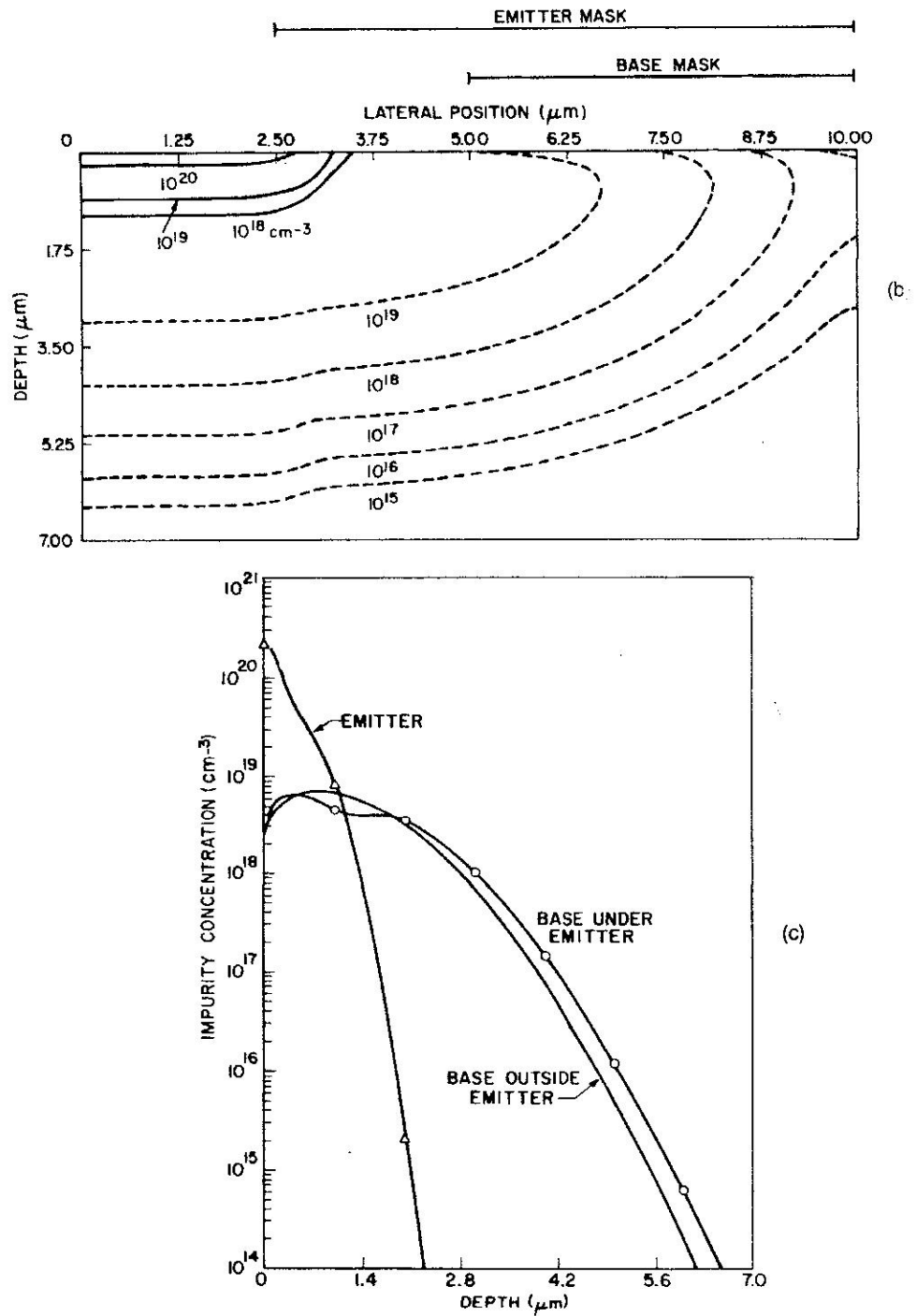


Fig. 13 (continued) (b) Contour plot of phosphorus and boron concentration. (c) Phosphorus and boron profiles in the emitter and the inactive base region. (After Penumalli, Ref. 25.)

Base formation For a given emitter profile, the lower the total integrated charge is in the active base (Gummel number), the higher the current gain is.⁶ However, if the base charge is too low it cannot support the reverse-bias voltage which is applied across the collector-base and/or emitter-base junctions. This results in unwanted "punchthrough" current. Also as the base charge is reduced, the output characteristics (i.e., collector current vs. collector-emitter voltage) exhibit steeper slopes (low output impedance), which may be undesirable in circuit applications. The narrower the base is, the shorter is the diffusion time of minority carriers across the base. As the base is made narrower for better performance, the doping level must therefore be raised to prevent punchthrough. In high-frequency bipolar transistors, the base doping profile is graded from a high to a low value from emitter to collector. This profile creates a built-in electric field in a direction that aids the transit of minority carriers across the base. Typical base Gummel numbers are in the 10^{12} to 10^{13} atoms/cm² range.

The extrinsic-base region (Fig. 2) must be adequately doped to provide a low-resistance path to the active-base region. If the extrinsic base is doped too heavily, however, excessive emitter-base capacitance will result along the emitter sidewall and a low emitter-base reverse-breakdown voltage may result. The active- and extrinsic-base regions can be formed by a single ion-implantation step, as shown schematically in Fig. 4a. Alternatively, a double-base implant can be employed as shown schemati-

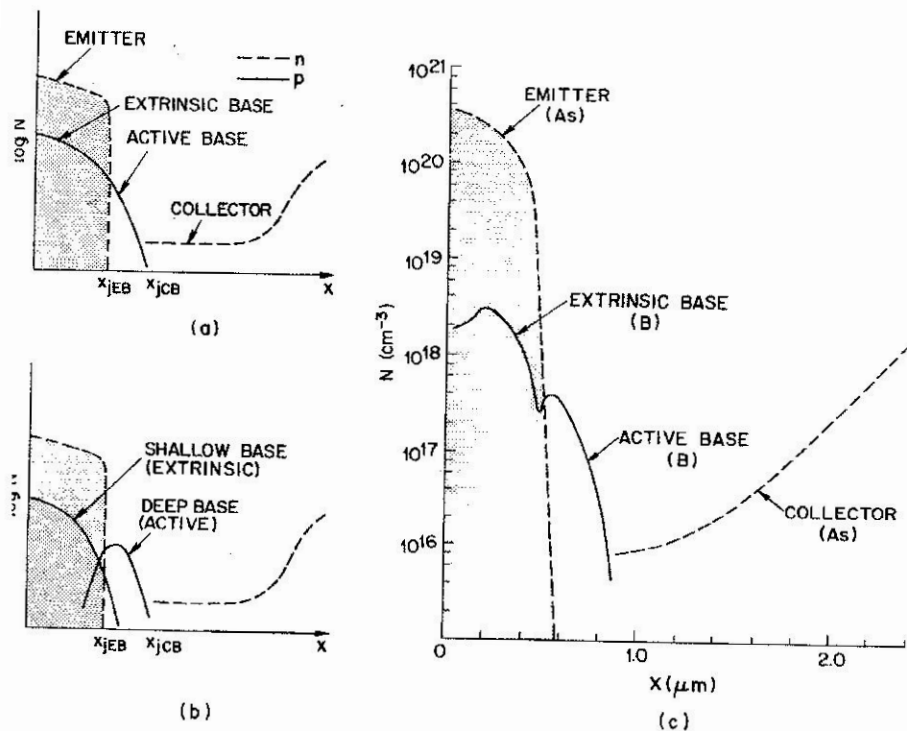


Fig. 4 n-p-n transistor doping profiles. (a) Single-base implant (schematic). (b) Double-base implant (schematic). (c) Single-base implant (actual).

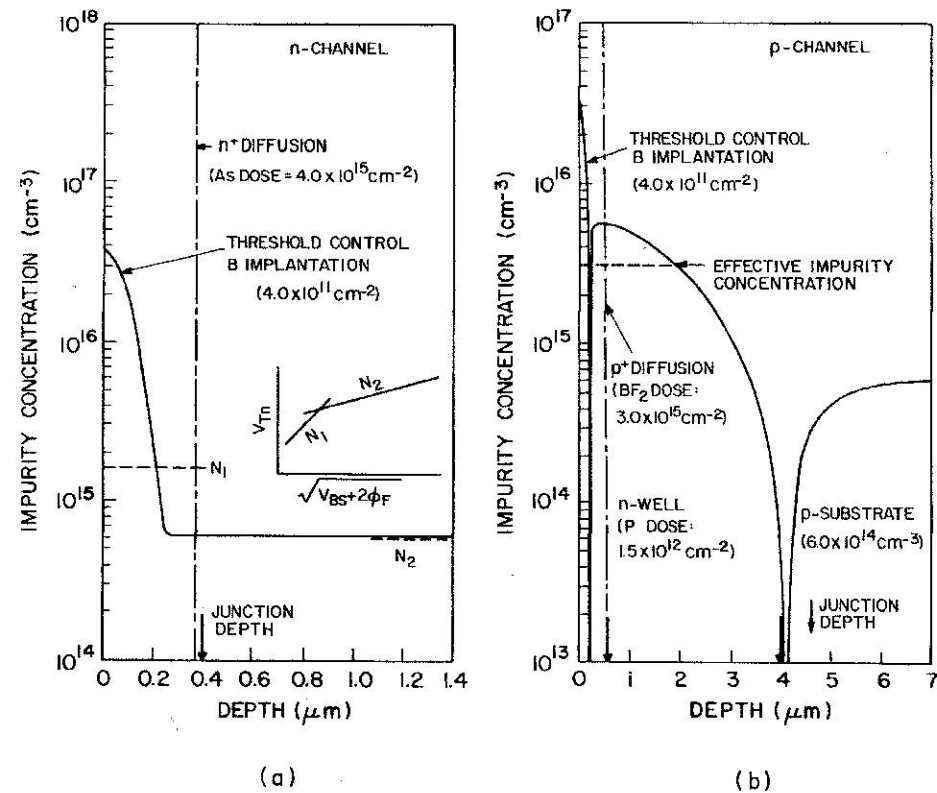


Fig. 33 Calculated impurity profiles under the gate. (a) n-channel device with 6×10^{14} atoms/cm³ p-substrate doping, and 4×10^{11} atoms/cm² boron threshold-adjustment implant. The n⁺ source/drain junction depth (0.4 μm) is indicated. The insert shows the threshold voltage sensitivity to back-gate bias due to the high-low doping profile. (b) p-channel device in an n well with the same boron threshold-adjustment implant. The p⁺ source/drain junction depth (0.55 μm) is indicated. (After Ohzone et al., Ref. 55.)

The desired threshold voltages of $V_{Tn} = -V_{Tp} = 0.7$ V are obtained by using an n-well phosphorus dose of 1.5×10^{12} atoms/cm² and a threshold-adjustment boron dose of 4×10^{11} atoms/cm². For these conditions, the calculated impurity profiles under the gate for each type of device⁵⁵ are shown in Fig. 33a and b. The n MOSFET uses arsenic for the source/drain impurity. Its threshold sensitivity to back-gate bias is initially steep and then less sensitive at larger values of V_{BS} (see insert in Fig. 33a)—which is a consequence of the high-low doping profile under the gate. The p-channel device (Fig. 33b) uses BF₂ for the source/drain because it results in a shallower implant depth than B. Note that, as a result of the threshold-adjustment implant, a net p region exists at the surface of the p-channel device and connects the p⁺-source/drain regions. This structure is analogous to a normally off, buried, n-channel MOSFET. That is, the work-function difference of the n⁺-polysilicon gate in the device of Fig.