

VLSI Handbook

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Chapter 27

Plasma Processing for VLSI

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INTRODUCTION I

The introduction of plasma processing to the manufacture of integrated circuits over the last 15 years has contributed significantly to the advent of VLSI. Plasma-assisted etching techniques have replaced chemical etching, particularly where strict dimensional control is required. Sputtering has replaced evaporation for the deposition of metals, and plasma enhanced chemical vapor deposition (PECVD) is providing an attractive alternative to conventional atmospheric and low pressure CVD methods.

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II ETCHING

In this section the basic principles of plasma-assisted etching are introduced. Melliard-Smith and Mogab [1] have reviewed the subject, and the mechanisms of these processes have been discussed in detail by Flamm *et al.* [2]. Reviews of specific techniques such as reactive ion etching [3] and ion milling [4] are also available.

A Anisotropy

The greatest advantage of dry or plasma-assisted etching processes over wet chemical etching techniques for VLSI circuit fabrication is the superior dimensional control. Fundamental to dimensional control, the accurate replication of a photoresist feature into the underlying film, is the concept of anisotropy. In an anisotropic etch, the rate of etching perpendicular to the wafer surface is much greater than that lateral to the surface. In an isotropic etch, the etching rates are equal in both directions, which causes undercutting of the masking material and a change in dimension of the etched pattern by at least twice the film thickness.

B Selectivity

In addition to a degree of anisotropy, a VLSI etching technique requires selectivity of the film to be etched over both the masking resist and the often thin underlying substrate. Further, the best results have been obtained when the etch yields volatile products which can be removed by the plasma reactor vacuum system. The requirements for selectivity and volatile etch products have led to the use of gases containing halogens (F, Cl, and Br) as plasma etchants. In the plasma environment, compounds made up of the halogens as well as carbon, sulfur, nitrogen, silicon, or hydrogen dissociate to form reactive atoms, radicals, and ions which participate in the etching reactions. These plasmas have been conveniently grouped into those that primarily generate free F atoms, unsaturated fluorocarbons, and those generating Cl and Br species [2].

C Etch Profiles

Four types of etch profiles resulting from plasma-assisted etching processes are shown in Fig. 1.

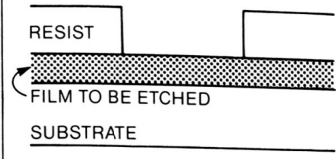
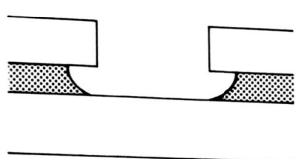
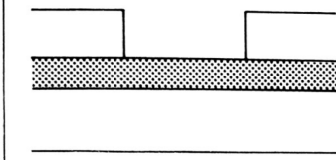
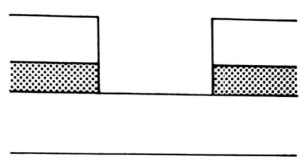
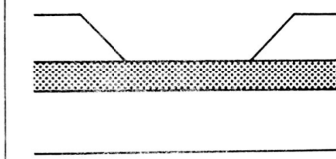
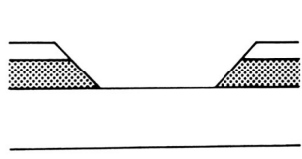
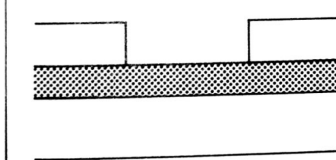

ETCH TYPE	INITIAL RESIST PROFILE	PROFILE AFTER ETCH
(a) SELECTIVE ISOTROPIC ETCH WITH NO RESIST EROSION		
(b) SELECTIVE ANISOTROPIC ETCH WITH NO RESIST EROSION		
(c) SELECTIVE ANISOTROPIC ETCH WITH SIGNIFICANT ETCH RATE OF TAPERED RESIST		
(d) NONSELECTIVE ANISOTROPIC ETCH		

Fig. 1. Etch profiles resulting from plasma-assisted etch processes.

(a) A selective isotropic etch with little or no etching of the initial resist pattern yields an undercut profile (Fig. 1a). Dimensional control is difficult with this type of etch, because after the film has been cleared, lateral etching often occurs at an increased rate due to the increased availability of reactant.

(b) A selective anisotropic etch results in excellent pattern transfer from resist to underlying film (Fig. 1b).

(c) The application of a selective anisotropic etch prepares a controlled slope on the edge of the etched film (Fig. 1c). Plasma parameters are adjusted so that the resist has a significant anisotropic etch rate, resulting in the transfer of the original resist profile into the underlying material. This technique can be useful when the steep step prepared by method (b) would complicate patterning of subsequently deposited films.

(d) The results of a nonselective anisotropic etch are shown (Fig. 1d). Due to the sputtering nature of this process, significant erosion of the resist and underlying film has occurred, as well as a change in pattern dimension.

D Equipment

Four basis types of equipment used for plasma-assisted etching are shown in Fig. 2.

(a) In a *barrel etcher* (Fig. 2a), the plasma serves only to produce reactive etchant species [2]. The plasma is often isolated from the wafers by an etch "tunnel," leaving the reactant species to reach the wafers by

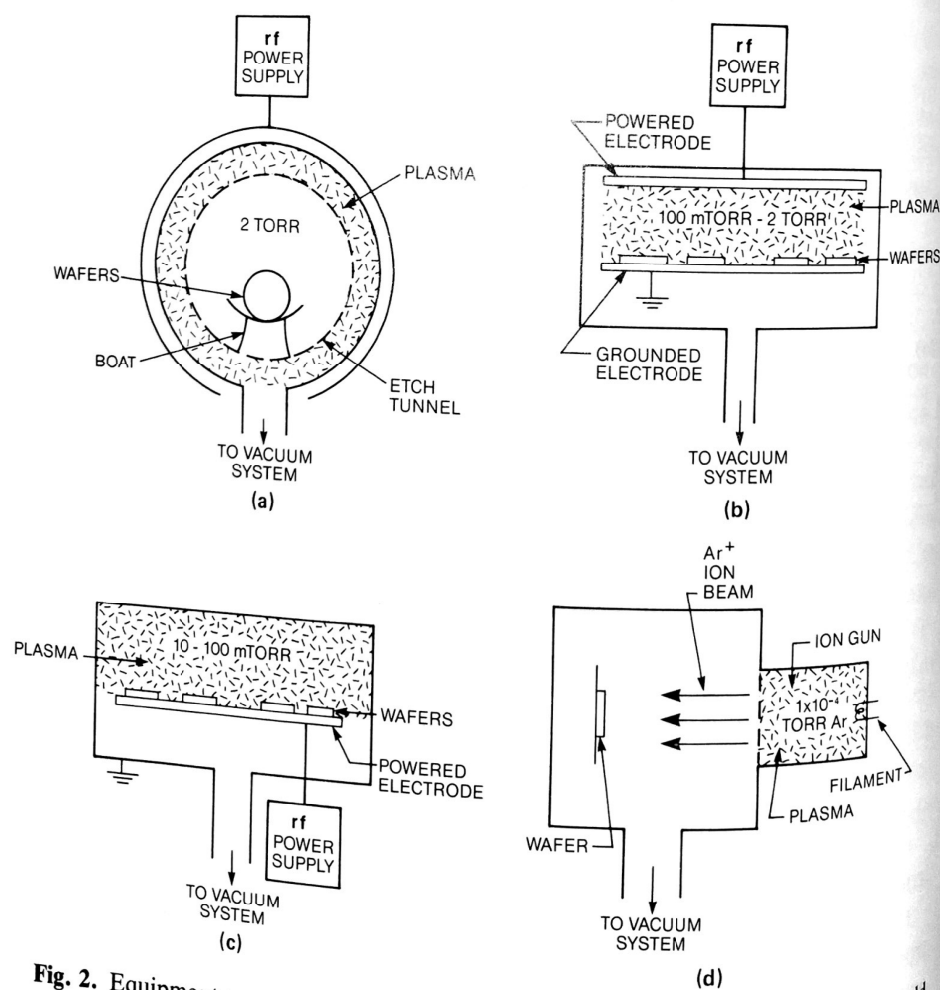


Fig. 2. Equipment used for plasma-assisted etch processes (for simplicity, the manifold used to introduce the etch gases into the system is not shown). (a) Barrel etcher. (b) Planar plasma (or diode) reactor. (c) Reactive ion etcher. (d) Ion milling apparatus.

diffusion. The design of this reactor and the high pressures usually used result in isotropic etch profiles. Si_3N_4 and polycrystalline Si can be etched with this type of equipment, but its most common use today is in photore-sist stripping.

(b) In a *planar plasma* (or *diode*) *reactor* (Fig. 2b), the wafers are loaded on the grounded electrode.

(c) In a *reactive ion etcher* (RIE) (Fig. 2c), the wafers are loaded on the powered electrode. The difference in size of the grounded electrode (the whole chamber) and the powered electrode, coupled with operation at low pressure (<100 mTorr) cause a negative dc bias to appear on the powered electrode of the RIE system. This causes significant positive ion bombardment of the electrode surface, resulting in an ion-assisted anisotropic etch. Though the planar plasma etcher shown in Fig. 2b operates at a higher pressure (100 mTorr–several Torr), it can be made to produce significant ion bombardment and hence anisotropy by using a reduced frequency (<1 MHz). For a discussion of this point, see Ref. 2. Both the planar etcher and the reactive ion etcher schematically described in Figs. 2b and c are popular for patterning films where dimensional control and selectivity are required, such as Si (polycrystalline and single crystal), SiO_2 , and Al alloys.

(d) In an *ion milling apparatus* (Fig. 2d), the ion producing plasma is isolated from the sample to be etched. An ion beam is produced and directed onto the sample, resulting in a purely physical etching process and an etch profile such as that shown in Fig. 1d.†

Parameters Affecting Anisotropy and Selectivity E

Many parameters affect the anisotropy and selectivity of a plasma-assisted etch. Most important are the chemical nature of the reactant gas or gases, the reactor type, gas pressure, and applied rf power and frequency. The gas flow, electrode materials and spacing, wafer temperature, and number of wafers etched at one time (loading) can also have significant effects.‡

Mechanisms for Producing Anisotropy and Selectivity F

The mechanisms active in producing anisotropy and selectivity in plasma-assisted etching processes have been described in detail in Ref. 2.

† For a review of this type of ion etching, see reference [4].

‡ For detailed discussions of these parameters, see references [1–4].

Briefly, anisotropy as produced by positive ion bombardment can be achieved by three mechanisms.

- (a) Ions can sputter adsorbed reaction products from the surface.
- (b) Ions can produce lattice damage, creating more active sites for reaction.
- (c) Ion bombardment can remove an adsorbed layer that inhibits etching (by reacting with the etchant or simply by inhibiting access to the surface by the etchant).

Since the ions are directed perpendicular to the surface, all three mechanisms result in anisotropic etching as described in Fig. 1b. Selectivity is more difficult to engineer into an etch process. One method is to adjust the plasma parameters and etch-gas chemistry so that one material is essentially only physically sputtered whereas the other is etched at an enhanced rate by chemical reaction. Alternatively, when chemical reaction limits the selectivity, the etch-gas composition can be adjusted to favor the chemically enhanced etching of one material over the other. Selectivity is most often achieved empirically.

TABLE I
Summary of Plasma Etching with F-Atom Source Plasmas

Materials	Gases	Anisotropy	Selectivity
Si	F ₂ , CF ₄ -O ₂ , C ₂ F ₆ -O ₂ , C ₃ F ₈ -O ₂ , SF ₆ - O ₂ , SiF ₄ /O ₂ , NF ₃ , ClF ₃	Isotropic	High over SiO ₂ , Si _x N _y , metals, silicides
SiO ₂		Isotropic at low ion energy; anisotropic at high ion energies	Very high over III- V compounds
Si _x N _y		Similar to SiO ₂	Selective over SiO ₂ in isotropic range
TiSi ₂ , TaSi ₂ , MoSi ₂ , WSi ₂		Partially aniso- tropic at high ion energies	High over SiO ₂ , Si _x N _y ; ~1:1 over Si
Ti, Ta, Mo, W, Nb		Anisotropic at high ion energies	High over SiO ₂ at high powers; selective over TaO ₂
Ta ₂ N		Isotropic at low ion energy	Selective over TaO ₂ , SiO ₂ , Al ₂ O ₃

TABLE II

Summary of Etching with Unsaturated Fluorocarbon Plasmas

Materials	Gases	Anisotropy	Selectivity
Si	CF ₄ , C ₂ F ₆	Partially anisotropic at low pressure, high ion energy	—
SiO ₂ , Si _x N _y	CF ₄ , C ₂ F ₆ , C ₃ F ₈ , CHF ₃ , CF ₄ or C ₂ F ₆ with H ₂ , CH ₄ , C ₂ H ₂ , or C ₂ H ₄ additions	Anisotropic at high ion energies	High over Si and III-V compounds
TiO ₂ V ₂ O ₅			High over Ti High over V

TABLE III

Summary of Plasma Etching in Chlorine- and Bromine-Containing Plasmas

Materials	Gases	Anisotropy	Selectivity
Si	Cl ₂ , CCl ₄ , CF ₂ Cl ₂ , CF ₃ Cl, Cl ₂ /C ₂ F ₆ , Cl ₂ /CCl ₄ , Br ₂ , CF ₃ Br	Anisotropic at high and low ion energies; isotropic for doped Si under high pressure conditions with pure Cl ₂	High over SiO ₂
III-V Compounds	Cl ₂ , CCl ₄ , CF ₂ Cl ₂ , CCl ₄ /O ₂ , Cl ₂ /O ₂ , Br ₂	Anisotropic at high and low ion energies (for chlorocarbon and BCl ₃ mixtures); isotropic for Br ₂ and Cl ₂ under some conditions	High over SiO ₂ , Al ₂ O ₃ , Cr, MgO
Al	Cl ₂ , CCl ₄ , SiCl ₄ , BCl ₃ , Cl ₂ /CCl ₄ , Cl ₂ /BCl ₃ , Cl ₂ /CH ₃ Cl, SiCl ₄ /Cl ₂	Anisotropic at high and low (for chlorocarbon mixtures and BCl ₃) ion energies; isotropic for Cl ₂ without surface inhibitor	High over Al ₂ O ₃ and some photoresists
Ti Cr CrO ₂ Au	Br ₂ Cl ₂ /O ₂ /Ar CCl ₄ /O ₂ /Ar Cl ₂ /Ar, CCl ₄ /Ar C ₂ Cl ₂ F ₄ , Cl ₂	Anisotropic at low ion energies	1 : 1 vs CrO ₂ at >20% O ₂ High vs Cr