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DRY ETCHING OF METALLIZATIONS

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The production dry etch processes from the perspective of microelectronic fabrication applications are reviewed. While for semiconductors, the term "metallization" is generalized to include all conductors, particularly doped polysilicon, the only actual metals extensively used in the large volume semiconductor applications are aluminum based. Aluminum in these applications is in the form of an alloy with silicon (usually 1%) and/or copper (up to 4%) and sometimes in conjunction with a barrier metal such as titanium to prevent diffusion of silicon. Consequently, recent work in dry etching of metals has been concentrated on developing reliable production processes for the aluminum based metallizations. And, only within the past two years, has dry etching of aluminum emerged from the laboratory into production, primarily because of progress in Reactive Ion Etch mode plasma systems, (discussed below) along with the associated gas chemistries.

For dry etching, applications are to thin films with thicknesses usually less than 2 microns and with a pattern defined by a photo resist mask. Dry etching provides the advantages of (1) eliminating disposal of hazardous chemicals, (2) etching materials that are difficult to wet etch, and (3) etching patterns with vertical walls, that is, etching anisotropically. Anisotropic etching is essential to advanced microelectronic devices because: (a) undercut limits line width sizes and corresponding "packing density", (b) loss of cross-sectional area of a conductor causes increased resistance, and (c) a negative slope type undercut, as tends to occur if aluminum etching is not fully anisotropic, makes step coverage by a subsequent layer difficult. For a dry etch application, etch quality criteria which should be considered are: the degree of anisotropy, etch selectivity (with respect to mask and underlying layer), etch uniformity, residue after etching (compare figures 1 and 2) corrosion after etching (a critical consideration with aluminum), thruput requirements, and process reliability.

The major dry etch processes used in the fabrication of microelectronic devices, given in figure 3, can be divided into two categories - Plasma processes in which samples are directly exposed to an electrical discharge, and Ion Beam processes in which samples are etched by a beam of ions extracted from a discharge. The plasma etch processes can be distinguished by the degree to which ion bombardment contributes to the etch process. This, in turn is related to capability for anisotropic etching. Reactive Ion Etching (RIE) and Ion Beam Etching are of most interest for etching of thin film metals. RIE is generally considered the best process for large volume, anisotropic aluminum etching.

Barrel Type Plasma Etchers

The Barrel Type plasma etch configuration, sch[illegible] figure 4, is usually a quartz cylinder into which wafers are loaded concentric to the cylinder axis. An RF discharge, with fields applied external to the reactor vessel, fragments the gas into chemically reactive species. A shielding screen may be used to prevent the ionized gas from reaching the wafers. Etching is then primarily, or entirely, by neutral, chemically reactive species. The advantages of barrel type reactors are their high throughput at a low capital cost. The disadvantages are that etching is purely chemical, and therefore isotropic, and that materials for which bombardment is needed to contribute to the etch process (eg. SiO_2) are difficult to etch.

Plasma Mode and RIE Mode Plasma Systems

Plasma Mode and RIE Mode planar electrode configurations, figures 5 and 6, have two important differences: (1) RIE operates at a lower pressure (<200 microns), and (2) for RIE, the wafers sit on a capacitively coupled, RF driven electrode, while for the plasma mode, wafers are on a grounded electrode. In the RIE mode, wafers being etched can take on an average negative self bias voltage with respect to the plasma and, as a result, energetic ion bombardment (in the range of several hundred eV as opposed to less than 50 eV for Plasma mode operation) can contribute to the etch process. The energetic ion bombardment provides the RIE process with its anisotropic etch capabilities (figure 7). Anisotropic etching is possible in the Plasma mode but such processes are much more dependent on polymerization processes to protect the pattern sidewall from undercut than in RIE processes.

As with the barrel etch process, in Plasma mode and RIE chemically reactive species are created by the RF discharge. However, etch mechanisms, and hence etch characteristics, differ as a result of the degree of ion bombardment. In RIE processes for Aluminum, the chemically reactive species are chlorine species produced by fragmentation of molecules containing chlorine (ie. BCl_3, CCl_4, Cl_2, $SiCl_4$). The surfaces which are etched, those parallel to the electrode to which the wafers are affixed, continuously undergo ion bombardment which cleans the surface of native oxide, or any other reaction inhibiting layer (figure 7). Directional etching can then proceed by the reactive chlorine species forming aluminum chlorides which, having a low vapor pressure, can be pumped away.

Fully automated, cassette-to-cassette, load locked Plasma and RIE mode systems are available. Plasma mode systems, by virtue of their higher operating pressure can have much higher etch rates, thus single wafer at a time as well as batch systems are made. Figure 8 shows the Veeco DV-40 cassette-to-cassette, load locked RIE system for large volume aluminum, SiO_2 and polysilicon etching.

Ion Beam and Reactive Ion Beam Etching

Ion beam etching is accomplished by a collimated beam of ions which is extracted from a discharge by a set of grids (figure 9). Substrates to be etched are affixed to a target plate which must preform the multiple functions of: (1) heat sinking the wafers being etched to prevent overheating, particularly of resist, (2) tilt at an angle with respect to the incident ion beam to give control over the pattern sidewall characteristics, and (3) rotate in the ion beam to symmetrically average the affect of the tilt on the pattern being etched. Ion beam systems operate at a low pressure, about $1X10^{-4}$ Torr, to eliminate ion beam - gas molecule collisions in the etch chamber from affecting the etch process. Vacuum pumping by means of a diffusion or cryopump is needed, when using reactive gases cryopumping is generally not acceptable.

For inert gas Ion Beam Etching, in which argon is commonly used, the etch process is purely mechanical sputtering. The sputtering rate is a function of the binding energy between the atoms in the surface being etched. In the case of Reactive Ion Beam Etching, reactive species can chemically change the bonding of the surface atoms thus changing the etch rate. When using the reactive gas Cl_2, formation of weaker Al-Cl bonds on the surface can enhance the etch rate from the pure sputtering case of 400 Å/min to over 1,000 Å/min. When O_2 gas is used, stronger aluminum-oxygen bonding will depress the etch rate to less than 100 Å/min. The advantages of Argon ion beam etching are that: (1) Any material can be etched, in particular, chemically inert materials such as Ni-Fe (bubble memory and thin film magnetic head applications) and gold (high frequency transistor applications). (2) Combinations of materials, alloys and layers can be etched in a single step. (3) Pattern size that can be etched is limited only by the lithography. A characteristic making this process useful for etching electron beam written master chrome glass masks. And, (4) The slope of the pattern sidewalls can be controlled to give good step coverage for subsequent layers. Reactive Ion Beam Etching adds the capabilities of etch selectivity and higher etch rates.

Some of the capabilities of ion beam etching are shown by figures 10-12. In argon ion beam etching bubble memory patterns, figure 10, the aluminum conductor pattern can be etched with a sloped wall to provide step coverage for the subsequent dielectric layer. The Ni-Fe layer must be etched with spacings of less than 1 micron and with vertical walls to give well defined magnetic domains. Tantalum silicide ($TaSi_2$)/polysilicon double-layer "metallizations" which are of interest to replace doped polysilicon to give lower resistivity can be etched anisotropically in a single Reactive Ion Beam Etch process, fig figure 11, whereas anisotropic etching through both layers is difficult with Plasma and RIE processes, figure 12.

Ion Beam Etching has been used for lower throughput, "specialty" applications in which there are particularly demanding etch requirements. For a large ion beam etch system (eg. Veeco 10" Microetch, figure 13) an application in which 5,000 Å of Ni-Fe or 1 micron of gold are etched, the throughput would be about twenty-five 3" diameter or fifteen 4" diameter wafers/hr. Presently, ion beam etch systems with fully automated wafer handling are not available.

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Figure 1. RIE Pattern in 1.2-Micron Al and 2000 A Over SiO_2 (Photo Resist in Place)

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Figure 2. Plasma-Etched Pattern With Residue

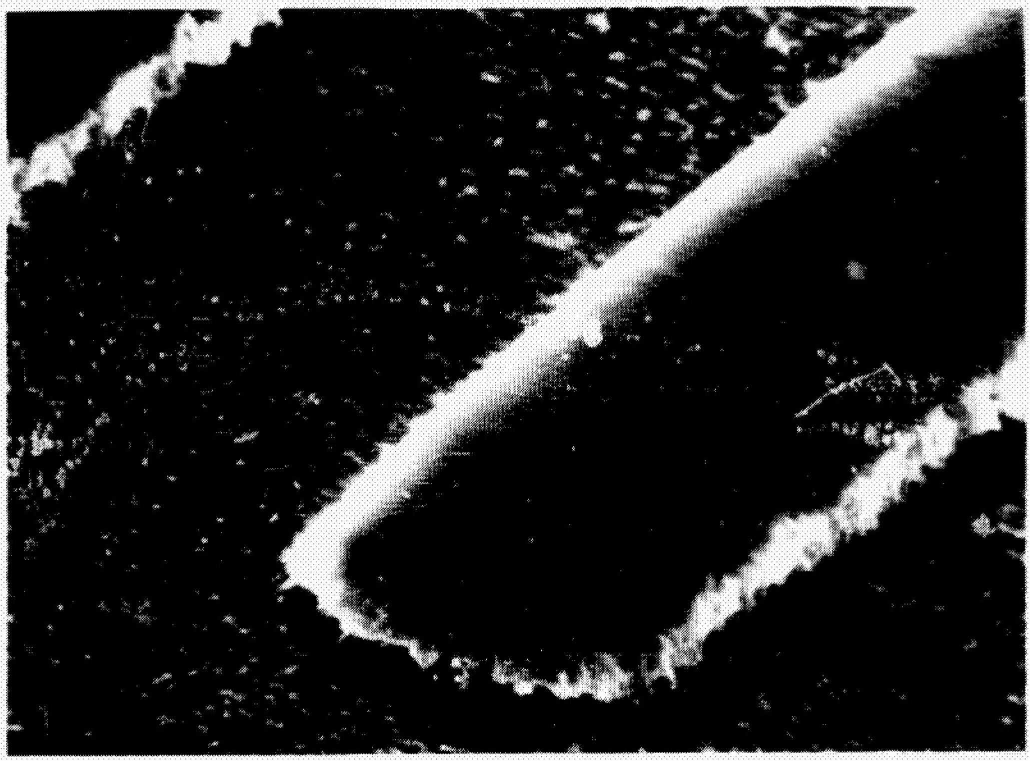

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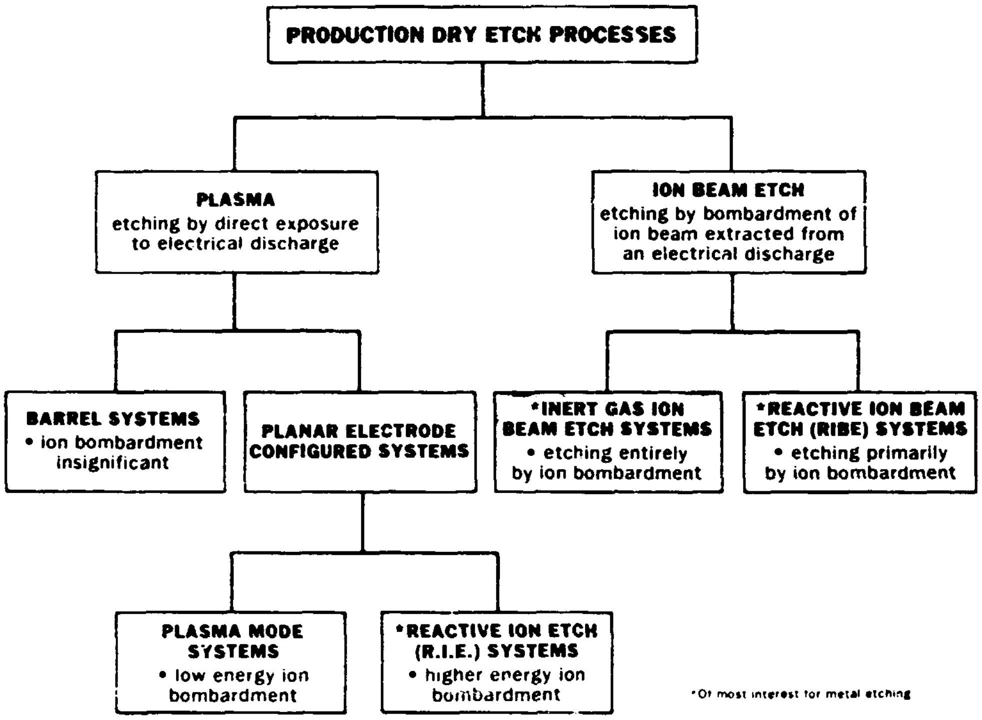
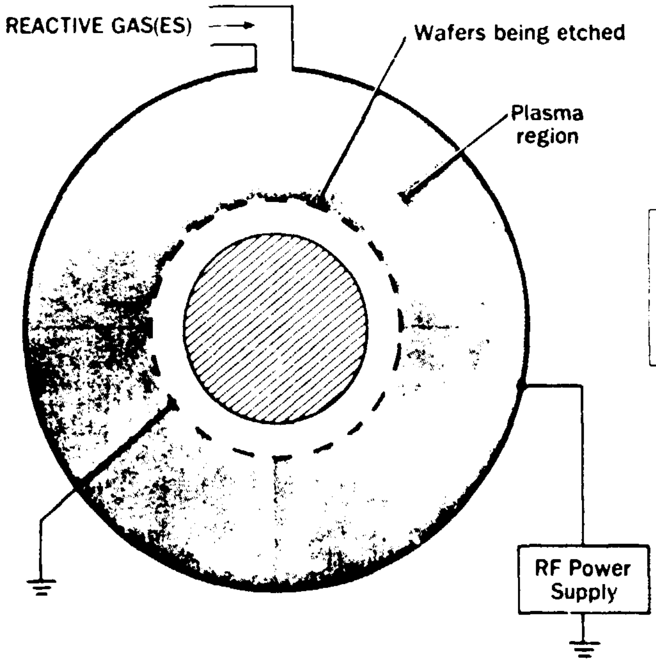
Figure 3.



*Of most interest for metal etching

Figure 4. Barrel-Type Plasma-Etch Configuration



Wafers etched by chemically reactive gas species created by electrical species

eg. silicon etch in discharge

$$CF_4 \longrightarrow CF_x + nF$$

on silicon surface

$$nF + Si \longrightarrow SiF_n$$

- isotropic etch (limited to large pattern geometries)
- high throughput
- low capital cost

Figure 5. Plasma Mode Type Etch System

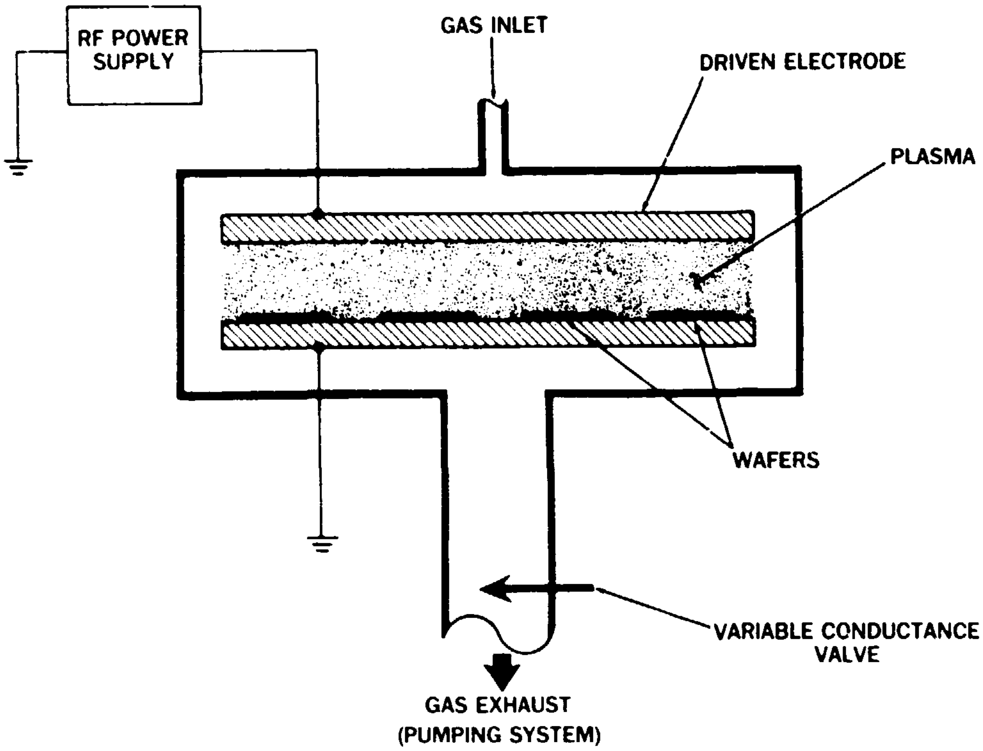


Figure 6. Reactive Ion Etch Chamber

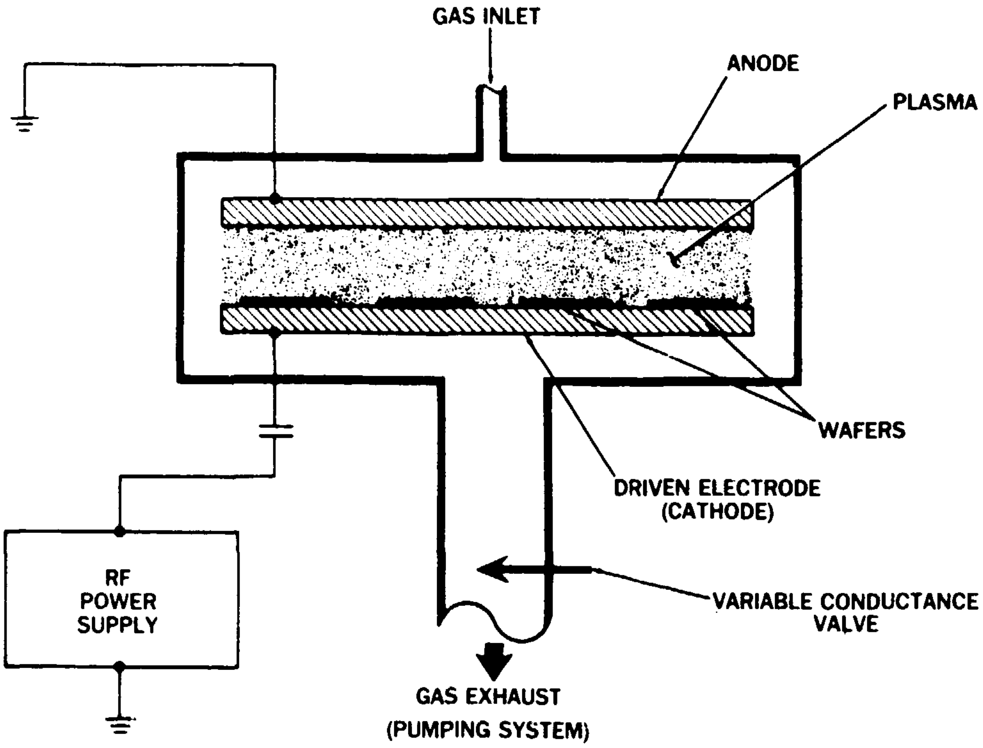
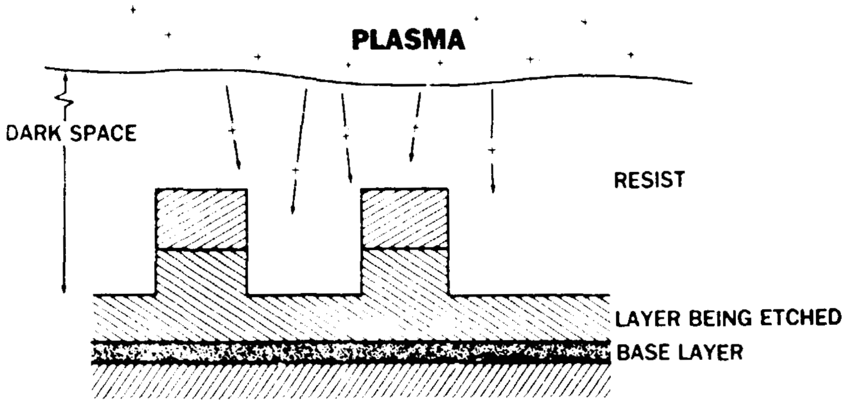


Figure 7.



REACTIVE ION ETCH PROCESS

1. RF discharge breaks up molecules creating ions and chemically reactive gas species
2. Horizontal surfaces "activated" by ion bombardment allowing chemical attack by reactive species.
    - anisotropic etch results from directional ion bombardment.
    - ion energy in range of 100 - 500eV.
3. When base layer reached, chemical selectivity results in low etch rate.
4. Etching stopped.

Figure 8. Veeco-Kokusai Reactive Ion Etch System

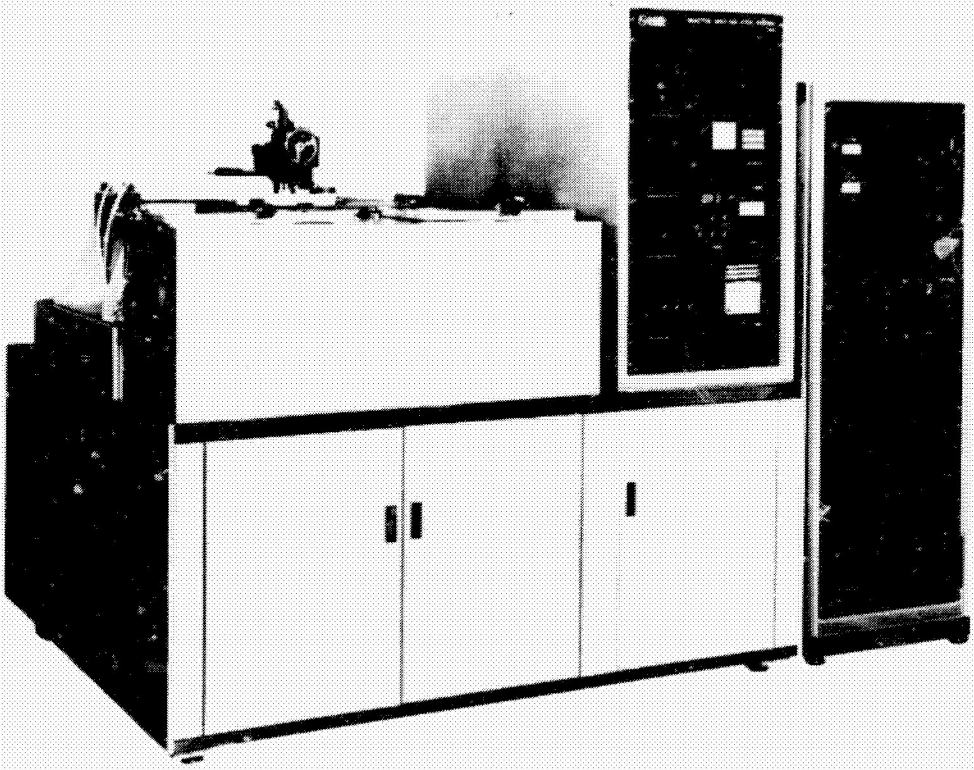


Figure 9. Production Ion Milling System

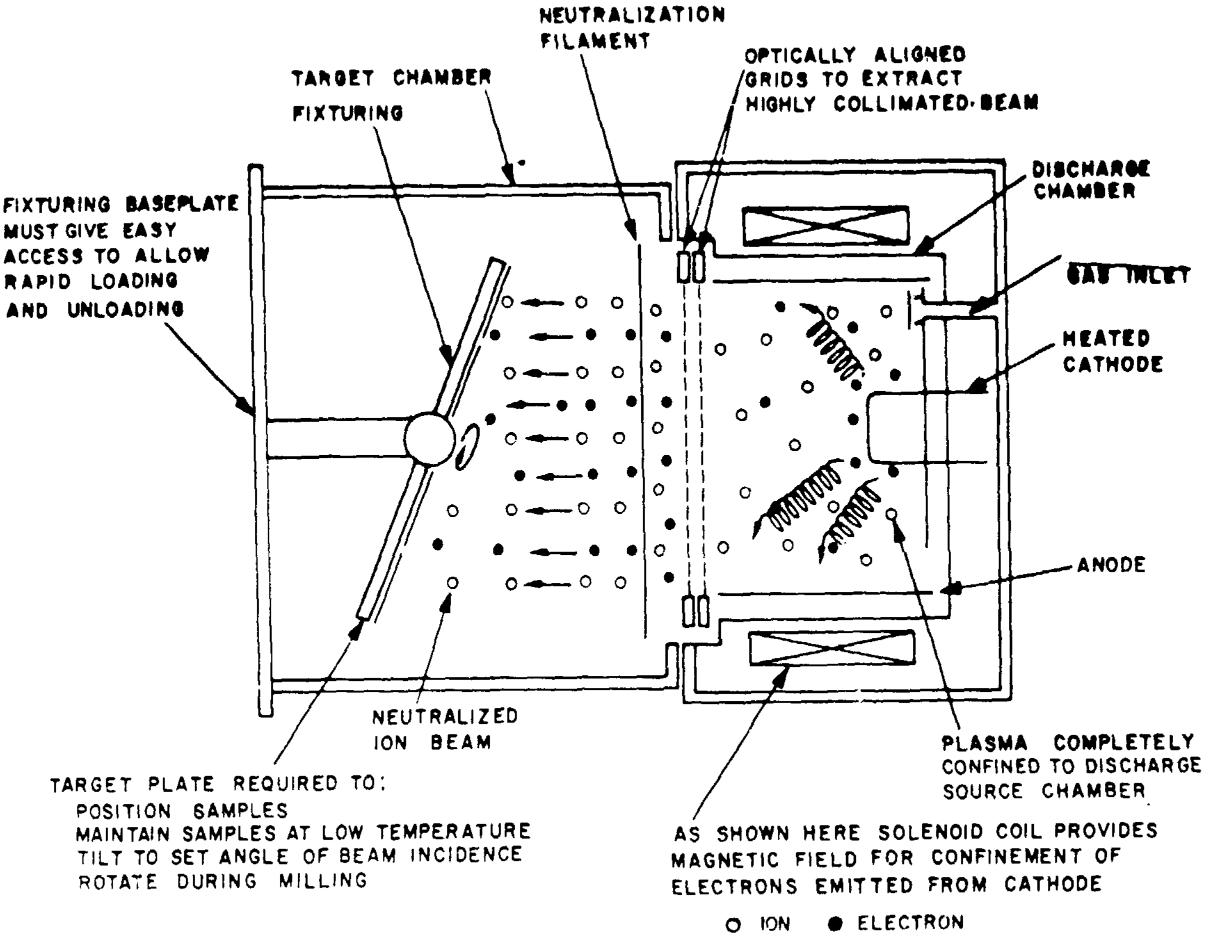


Figure 10. Bubble Memory Device Pattern Cross Section

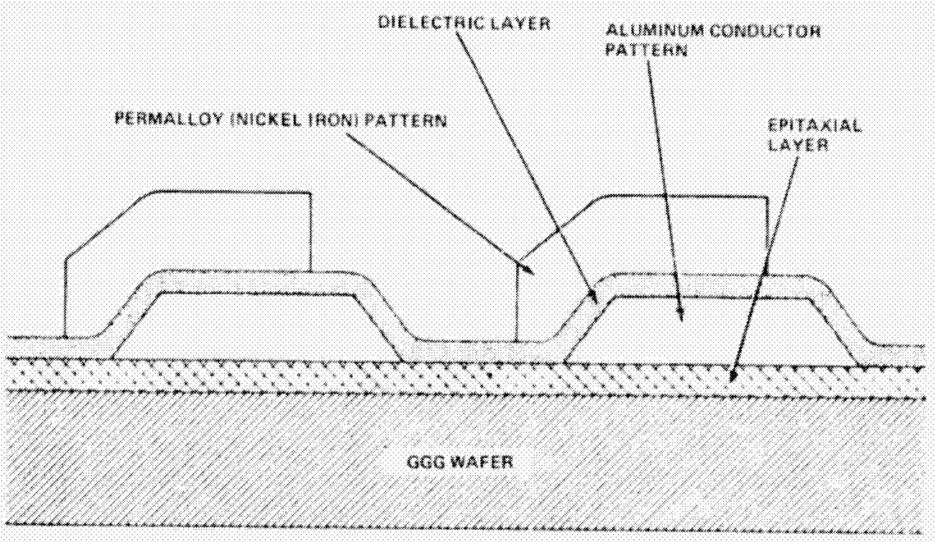


Figure 11. Reactive Ion-Beam-Etched $TaSi_2$-PolySi Structure

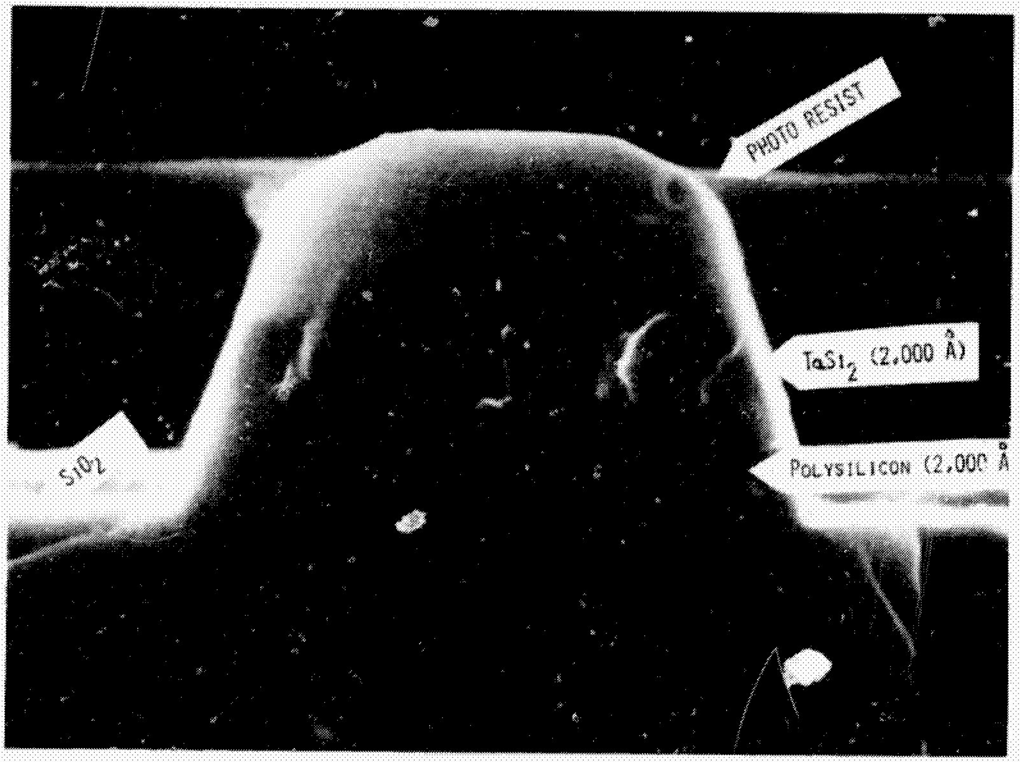


Figure 12. RIE of $TaSi_2$-PolySi (Using SF_6 Gas) Showing Undercut into PolySi Layer

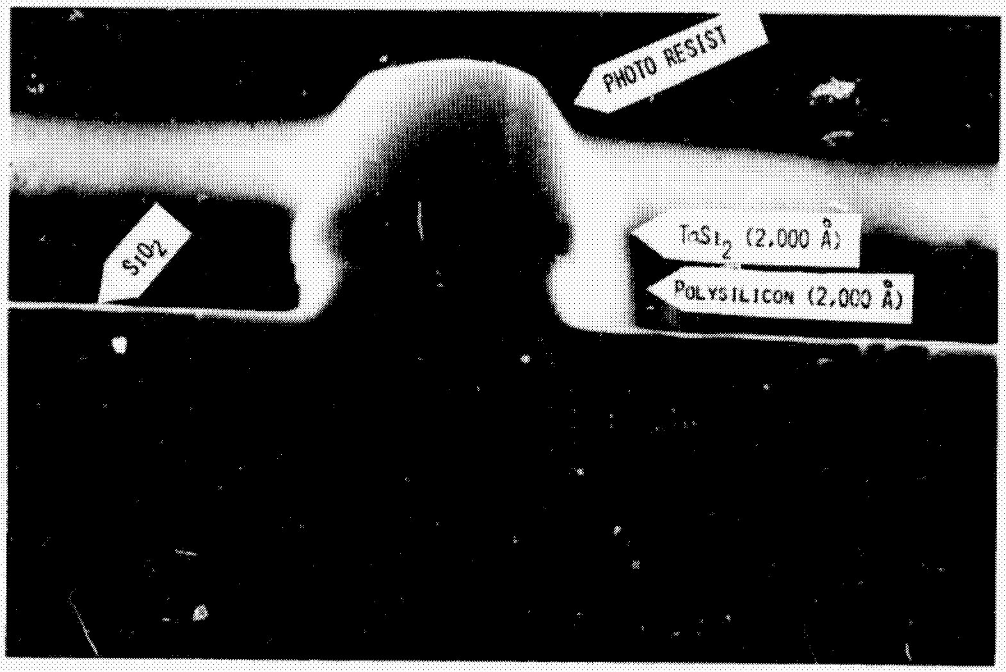
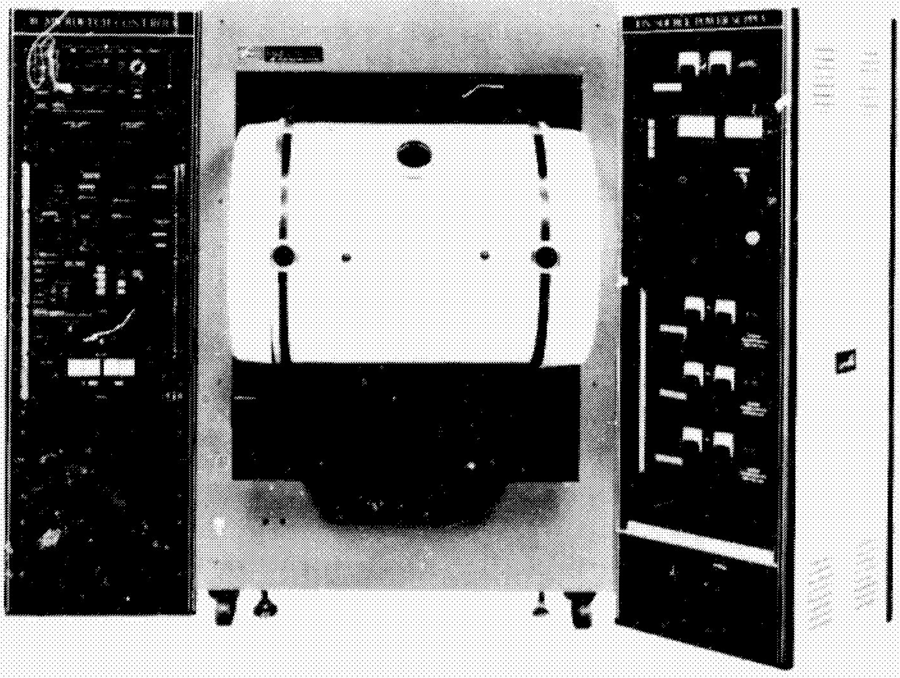


Figure 13. Veeco 10-in. Microetch Ion-Beam Etch System



DISCUSSION

GALLAGHER: Have you, in your travels, ever done any etching using shaped electrodes, to give you patterns without using photolithographic processes? For example, in our system, which you may or may not be familiar with, we had one of our contractors etch silicon nitride. We were using silicon nitride basically as an AR coating in this application and he wanted to make rather gross patterns, in relation to what you are doing, through the silicon nitride at the top of the solar cell, so that he could later plate contacts down in there and make his top contact. The gentleman who did some of it is sitting over in the corner. I just wondered if you had any history or knowledge of it.

BOLLINGER: Veeco hasn't done any direct etching without masking. We haven't done any specifically that I'm aware of. Both direct-writing etching and single-ion-beam etching were done through a mask, but not on a wafer directly.

GALLAGHER: Bob (Pryor), can you tell us a little bit about the conclusions Motorola reached on that?

PRYOR: We've used basically the parallel-plate type of method in the reactive ion mode, with a mechanical mask to actually shadow the impinging beam and etch where you want to etch without applying photoresist or any other kind of resist. That was the process developed on one of the former JPL contracts that we had. It works very successfully and worked quite well down to things on the order of about 1 mil in terms of line widths, which for our application is the size we were interested in.

BOLLINGER: Do you use a plate or something to shadow?

PRYOR: Yes, in effect, to put a shadow plate with a grid pattern in between the plasma and the substrate. It masks the accelerated ions and it works quite well.

AMICK: Can you say whether it is possible to monitor the progress of the etching by looking at the plasma emission?

BOLLINGER: Oh, yes. For plasma processes, a very good diagnostic tool, as well as for detecting end point, is optical emission spectroscopy, because you can look at a line, such as when etching aluminum or monatomic excitation lines. And the amount of the light emitted is basically proportional to the etch rate.

AMICK: Have you worked out any reactive ion etching techniques for diagnostic purposes using plasma emission?

BOLLINGER: Oh, yes. It is used in those techniques; in a reactive ion technique it works very well. Aluminum works very well; it's particularly good. In etching silicon dioxide you usually monitor the carbon monoxide line, which is not quite as good as the aluminum line, but those are very good diagnostic techniques for doing etching as well as monitoring end point.

AMICK: Are those built into the equipment?

BOLLINGER: It is built into the Veeco reactive ion system. In other equipment it would be an option, but it is an easily added option.

CAMPBELL: Is it safe to say that both the plasma mode and reactive ion-etching mode are line-of-sight etching?

BOLLINGER: You mean by the ions?

CAMPBELL: Yes.

BOLLINGER: I would guess it would be a line of discussion some people would agree with that with the plasma mode, because of the higher pressure and the many collisions suffered by ions in going through the sheath. But there has to be a directional aspect, certainly because it can give an isotropic etching, so it certainly would be safe to say that for the reactive etch mode people might argue it, but there is that aspect for plasma certainly.

CAMPBELL: So there would be "load factors" involved in both those cases. In other words, your etching has to be some way facing the beam.

BOLLINGER: Oh, yes. The beam is really formed in there, actually with the plasma and that cathode sheath, that dark space I mentioned, that forms around everything you put in a plasma. If you turn it in an angle it's going to form at an angle with respect to it, and you are going to get normal ion bombardment. You can't tilt it and get ion bombardment at another angle.

BURGER: Is there any area limitation in something like plasma planar reactors? For instance, you know you may make them 24 inches around because you are used to 24-inch bell jars. Why not 48-inch, or something like that?

BOLLINGER: I don't think there is any limitation. Very large systems have been made. For commercial sales they haven't done very well because of initial capital. I know of a company in Japan that made a 100-inch-diameter system and couldn't sell any because it was too big, but it can be done.

BURGER: Basically you would still get good process control and expect to turn out a good quality product.

BOLLINGER: Yes, you could. It would, of course, depend on making sure that the gas flow gave even etch gradients.

BURGER: It was the gas glow that was worrying me.

BOLLINGER: That would be a problem. The bigger you get the more deterrent it is, but it can be done. It has been done. I'm not sure how successful very large diameters are, but I'm sure it could be done.

SCHRODER: Which technique is the most used in IC production today?

BOLLINGER: If you just say silicon device production, it depends on the size. If you don't worry about anisotropic, certainly the barrel reactors are the most commonly used today. Most of IC production is 5 microns and in that range, but for the newer devices, so-called VLSI (Very-Large-Scale Integration), reactive ion etch and plasma mode are used almost exclusively.

SCHRODER: Ion beam is hardly used for the large application, is that right?

BOLLINGER: For the large-throughput applications, ion beam just doesn't have the throughput, and the plasma mode and the RE mode systems can handle the semiconductor materials well, so ion-beam equipment has not been developed for high throughput at this time.