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Microscopic and macroscopic uniformity control in plasma etching

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By cooling substrates to low temperatures (− 40 °C), plasma etching of AlGaAs/AlAs/GaAs structures is performed in an ion-activated, surface reaction limited regime. As a result, microscopic and macroscopic uniformity are vastly improved and etching is independent of gas flow patterns, plasma geometry, and reactor loading. Because the reactant is concentrated on the surface, etching rates remain large.

Nonuniform plasma etching can have serious consequences in microelectronic and photonic device fabrication. When etching is nonuniform, some areas clear before others and are exposed to the damaging plasma longer than desired. Such overetching also places severe constraints on selectivity; to preserve the device structure, other materials must be resistant to plasma etching. Two types of nonuniformity can be distinguished: macroscopic and microscopic. Macroscopic nonuniformity refers to etch rates that depend on position of the chip on the wafer or position of the wafer in the reactor, for example, etching is macroscopically nonuniform when the center of the wafer etches more slowly than the edge. Microscopic nonuniformity refers to etch rates that depend on the microstructure scale and geometry, for example, etching is microscopically nonuniform if small diameter contact windows etch more slowly than large diameter contact windows.

Most approaches to maximizing macroscopic uniformity have focused on control of gas flow, pressure, and reactor geometry. For example, both inward and outward radial gas flow designs have been used in parallel-plate batch reactors to achieve uniform etching or deposition across the electrode platen.[1] Besides flow geometry, reactor loading can also affect reactant concentration profiles and therefore etching rates and uniformity. Similarly, materials from which the reactor is constructed and materials such as masking layers can affect reactant concentrations, etching rate, and uniformity. Loading effects also produce nonuniform etching in single-wafer etchers where the gas flow pattern cannot be easily tailored. For example, in Al etching the wafer center usually etches more slowly than the wafer perimeter because of rapid reactant depletion.[2] In this case, guard rings and getter plates are used to surround the wafer and inhibit reactant flux to the wafer outer edge.[3] Although this approach is effective in solving the macroscopic uniformity problem, it is preferable to maximize throughput by enhancing the wafer-center etch rate. In addition, guard rings and getter plates can cause contamination by sputtering and thereby reduce device yield.

Unfortunately, such solutions to the macroscopic uniformity problem do not address the problem of microscopic uniformity at all. As feature dimensions have shrunk below 1 μm, etch rates have become increasingly dependent on pattern density and geometry. For example, in SiO_2 contact window etching, smaller windows etch more slowly than larger windows and overetching is routinely required to clear all windows. It is well known that both macroscopic and microscopic uniformity can be improved by reducing gas pressure. Macroscopic uniformity is improved because the plasma becomes more homogeneous and reactant transport to the surface becomes diffusion limited and independent of flow.

Three explanations have been offered for the improvement in microscopic uniformity at low pressure: (1) reduced ion scattering in the sheath, (2) enhanced reactant transport to the surface, and (3) enhanced product transport away from the surface.[4] Below 10 mTorr and for large electric fields, gas-phase ion scattering should not be an important factor affecting microscopic uniformity. Recently, Coburn and Winters have shown for most plasma etching conditions, typical submicron feature sizes, and typical etching rates that the effect of pressure on product transport is negligible.[4] On the other hand, they found that reactant transport into high aspect-ratio features could be limited even at low pressures and that this limitation could account for microscopic nonuniformities. They derived a phenomenological expression that related etch rate at the bottom of a feature with depth z and diameter d, $R(z/d)$, to the etch rate at the top of the feature, $R(0)$, to a microstructure-dependent transport parameter, $K(z/d)$, and the surface reaction probability, S:

$$R(z/d)/R(0) = K/(K + S - KS). \quad (1)$$

As seen from Eq. (1), when $S \gg K$, the reaction rate is gas phase transport limited and etching is nonuniform. Note that under these conditions, processes are subject to large loading effects, i.e., etching rate is dependent on wafer area.[5] When $S \ll K$, etching is both microscopically and macroscopically uniform. Thus, by using a polymerizing discharge, an etch-inhibiting layer could be used to slow the neutral reaction component and create an ion-activated, surface reaction limited regime.[2,6] This is a common solution used to achieve anisotropic plasma etching where the polymer is used to preferentially inhibit neutral-dominated side-wall reactions that undercut the mask.[6,7] Obvious problems with this approach are slower etching rate and contamination.

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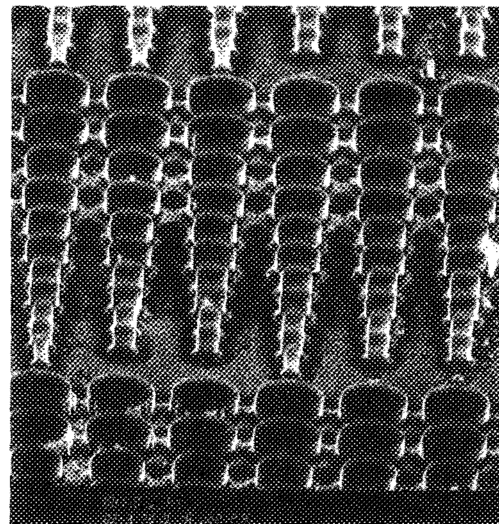
Recently, Tachi *et al.*[8] showed that highly anisotropic, selective etching could be achieved without sacrificing etching rate by cooling substrates (generally below 0 °C). Instead of using a polymer to inhibit etching where ions do not impact, substrate temperature is controlled so that neutral, thermally activated reactions are suppressed and only ion-activated chemistry occurs. Because the neutral chemistry is suppressed, only low ion energies are needed to achieve highly anisotropic and selective etching.

In this letter, we show that both microscopic and macroscopic uniformity can be improved without compromising etching rate by controlling substrate temperature. By making the substrate sufficiently cold, reaction becomes surface rate limited and *independent* of gas-phase transport. In particular, if the substrate temperature is adjusted so that multilayer reactant adsorption occurs but the reaction then stops,[9] then spontaneous etching only occurs upon ion impact. Since the reactant need not be supplied from the gas-phase, etching uniformity is controlled not by gas flow and pressure but rather by ion flux, which is naturally uniform at a planar surface in contact with a plasma. Since the neutral reactant exists at the surface, the etching rate can still be large. Thus, both S and K are effectively made larger where ions impact the surface but $S \ll K$ and rapid, load-independent, uniform etching is achieved.

To facilitate the measurement of microuniformity and macrouniformity, we use alternating 1000-Å-thick layers of $Al_{0.3}Ga_{0.7}As$ and AlAs grown by metalorganic chemical vapor deposition (MOCVD) on semi-insulating GaAs substrates. These multilayer post (or pixel) structures are useful for making devices such as microresonators, surface-emitting lasers, and quantum dots.[10] Sputtered SiO (5000 Å) is patterned using lift-off techniques to produce an array of microstructures with varying diameters (Fig. 1). On examination of the stuctures using a scanning electron microscope, $Al_{0.3}Ga_{0.7}As$ appears bright and AlAs appears dark. Thus, it is easy to determine etch depth to within 1000 Å.

Wafers are bonded to a temperature-controlled electrode using a thermally conducting compound (Omegatherm 201). (In a production environment, other methods of heat sinking the wafer, such as He back-side cooling and electrostatic chucking, could be employed.) Wafer temperature is monitored to within ±2 °C in real time using pulsed laser photoluminescence[11] and controlled to within 10–15 °C during the etch using a combination of liquid-nitrogen conduction cooling and resistive heating. The current electrode design is limited by low thermal conductivity of the stainless-steel electrode body so that when the plasma is initiated, the temperature rises slowly during the etch. Work is in progress to improve this design and achieve better temperature control.

A mixture of BCl_3 (5 sccm) and Cl_2 (0.5 sccm) is used to anisotropically etch the $Al_{0.3}Ga_{0.7}As$/AlAs multilayer structure at a pressure of 15 mTorr. rf power at 13 MHz is maintained at nominally 30±5 W but the plasma is not well confined and occupies a volume of approximately 4.8 ℓ. Typical voltages on the wafer electrode with respect to ground potential are 325 V peak with a −70 V dc offset. Both parallel-plate and perpendicular-plate electrode geometries are used but etching rate and uniformity are independent of reactor geometry. At low temperature, etching is surface reaction limited and uniform; at high temperature, etching is neutral reactant diffusive transport limited and nonuniform.


(a) Temp = 27 C

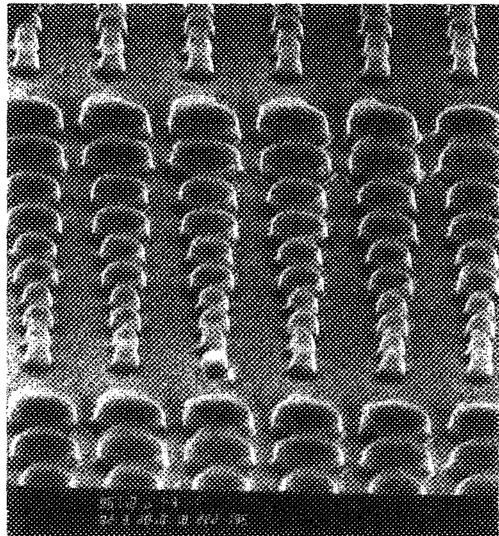

(b) Temp = - 40 C

FIG. 1. Anisotropic etching of AlGaAs/AlAs multilayer structure at (a) 27 °C and (b) −40 °C. Other conditions are 15 mTorr pressure, 30 W rf power, 5 sccm BCl_3, and 5 sccm Cl_2.

Results for etching a patterned wafer at different temperatures are shown in Fig. 1. It is clear that etching at lower temperature increases microscopic uniformity dramatically. At 27 °C [Fig. 1(a)], the average etched depth is 8500 Å but the etched depth varies by as much as four layers from closely spaced to widely spaced pixels. This corresponds to a microscopic uniformity of only 18–24%. Note that etching is still anisotropic everywhere. These results are consistent with ion activation of the surface by

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creation of a damage layer;[7] the overall etching rate would then be limited by diffusive transport of neutral reactive species.

At $-40\,^{\circ}\mathrm{C}$ [Fig. 1(b)], etching is anisotropic but etched depths differ by less than a single epitaxial layer everywhere on the wafer; this corresponds to a microscopic uniformity of $<3\%$. This upper bound is consistent with the nonuniformity expected in MOCVD growth. As expected, this result does not change when the wafer area (reactor loading) is changed by four times since the reaction rate is controlled by surface processes and not by gas phase transport. Similarly, uniformity is unaffected by reactor geometry (both parallel-plate and perpendicular-plate electrode geometries yield the same results) and gas-flow patterns.

Similar improvement in uniformity is observed in the macroscopic etching pattern (Fig. 2). At high temperature, a "bulls eye" edge-to-center clearing pattern is indicative of a reaction that is limited by diffusive transport.[2] Macroscopic uniformity can be achieved by cooling the substrate so that the rate is surface reaction limited [Fig. 2(b)]. Under these conditions, uniformity is controlled only by ion flux.

Etching rates for this structure are 0.65 μm/min and 0.40 μm/min at 27 and $-40\,^{\circ}\mathrm{C}$, respectively. This small change in etch rate on cooling is similar to observations made during cryogenic etching of Si.[8] There, the insensitivity to etching rate with temperature was attributed to an increase in reactant sticking probability with decreasing surface temperature. Alternatively, a multilayer of reactant-rich material could be adsorbed onto the surface at low temperature. In this case, when the reaction is activated by ion impact, it can proceed rapidly because of an abundance of reactive material.

In summary, we have shown that both microscopic and macroscopic uniformity in plasma etching can be controlled by cooling substrates so that reaction rates are limited not by gas phase transport but rather by ion-activated surface reactions. Uniformity is no longer affected significantly by plasma geometry, gas flow, and gas pressure. Under these conditions, reaction rates are rapid and independent of reactor loading because reactive species are amply adsorbed onto the wafer surface. Similarly, etching should be insensitive to reactor and masking materials.

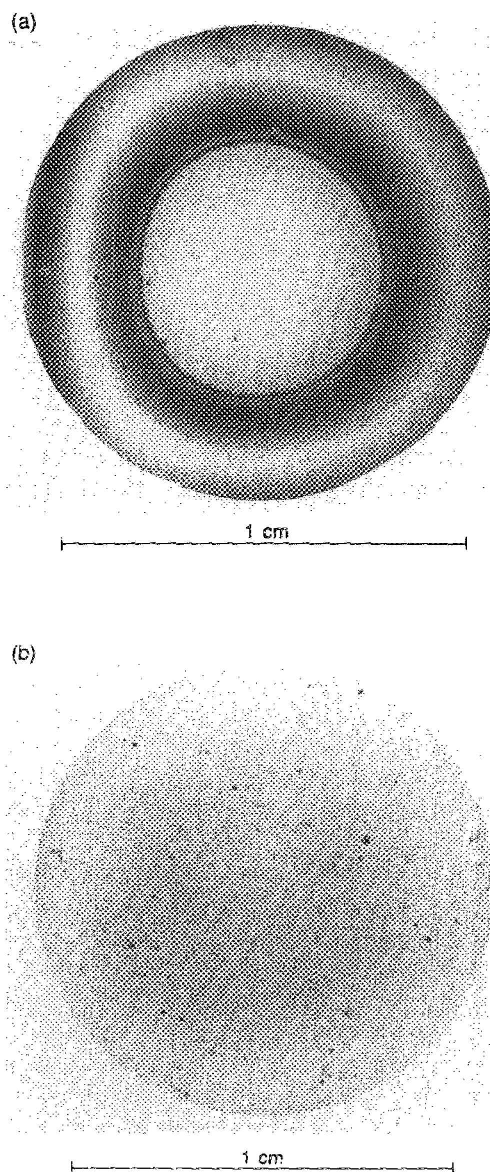

FIG. 2. Low magnification of unpatterned etched wafer as in Fig. 1 showing (a) "bulls eye" clearing pattern at high temperature and (b) good macroscopic uniformity at low temperature.

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