A source of hyperthermal neutrals for materials processing

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In this letter, we describe a unique method of producing hyperthermal neutrals for material processing. The hyperthermal neutrals are produced by accelerating ions across a sheath from a plasma onto a surface. On impact, the ions are neutralized and reflected with $\sim 50\%$ of their incident energy. These neutrals then bounce off of additional surfaces prior to impacting the target. This unique multiple bounce system was developed for the following reasons: to reduce contamination from sputtered surface material, improve beam uniformity, and reduce UV radiation in the beam path. As a test of this method, we built a prototype beam source and used it to ash photoresist at rates up to 0.022 μm/min. These rates are consistent with a predicted neutral beam flux, 2×10^{14} cm^{-2} s^{-1}. In addition, a simple model is used to indicate that this method is capable of producing economically acceptable ash rates. Comparisons with other neutral-beam production methods are made. © *1997 American Institute of Physics*. [S0003-6951(97)02433-9]

Plasma processing of materials is essential to many industries, particularly the semiconductor industry. In that industry, a feature size of 0.10 μm is envisioned by the year 2007.[1] At that size, plasma-induced damage may result in unacceptably high defect rates.[2–4]

Replacement of some plasma processing steps with hyperthermal-neutral beams may be necessary.[1] Kudryavtsev *et al.*[5] have reviewed methods for producing neutral beams. Typical parameters are in Table I. Combinations are common, e.g., effusion sources with ovens,[6] electron beams,[7] and laser radiation.[8] Recent neutral-beam-etching efforts are dominated by groups using either gas-dynamic or charge-exchange-based beam sources.[4,9–16]

Neutral beams produced by surface neutralization of plasma ions[17–20] appear to have the best potential for semiconductor processing, see Table I. For example, Cuthbertson[18] has reported a pulsed beam source with peak flux densities of $\sim 10^{18}$ cm^{-2} s^{-1} over several cm^2 and controllable energies from 1 to 25 eV. Finally, the chemistries[21] should be similar to those in plasma processing.

Our prototype neutral beam source, shown in Fig. 1, is based on the sources of Langer *et al.*[17] and Cuthbertson[18]. In those devices, the neutrals underwent only the initial neutralizing bounce. In our geometry, the neutrals undergo two (or more) bounces prior to arriving at the substrate. Thus, UV exposure of the substrate is low because it can be placed out of line-of-sight of the plasma. Additionally, the neutral flux is controlled by the microwave power; the beam energy is set by the cathode bias; and uniformity is controlled by geometry.

This prototype source employs an electron-cyclotron resonance discharge in a simple cylindrically symmetric planar magnetron geometry. Other geometries and plasma heating methods are possible. The magnetic field is provided by a single electromagnet. The microwaves are launched through a waveguide in the top flange of the chamber, 5 cm off center, with the electric field in the radial direction. While this launch geometry limits[22] the plasma density to $\sim 7 \times 10^{10}$ cm^{-3}, it still provides a simple test of the general method. The bottom flange is electrically isolated from the top of the chamber by an anodized Al ring, resistance $\geqslant 20$ MΩ. Gas is fed into the stainless steel chamber through a port in the side of the chamber. For some runs, a 1.9-cm long stainless-steel collimator was placed in the tube between the source and process chambers. The collimator has 73 evenly spaced, 0.635-cm diameter holes which account for 60% of the area. The platen consists of a black anodized Al base on ceramic electrical breaks and a metal mask. All of the data presented here was gathered when the wafer stage was electrically floating. The mask was used so that only a

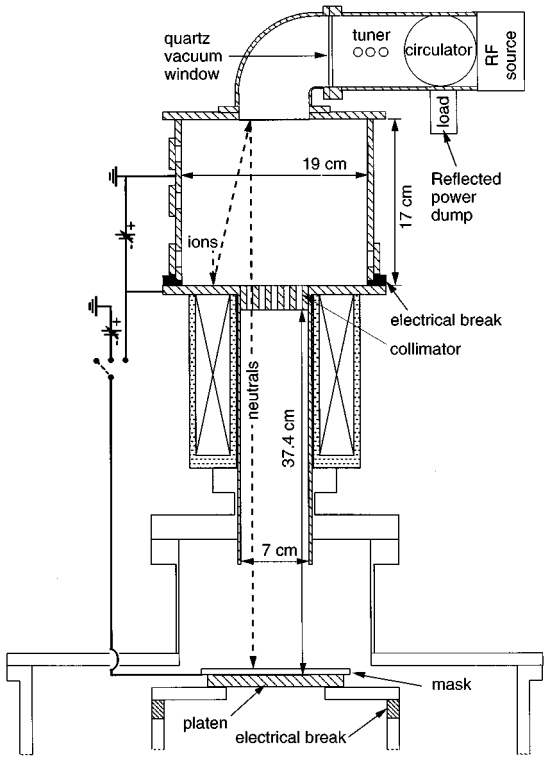

FIG. 1. Neutral beam source schematic. Neutrals, formed by ion impact on the bottom flange, emerge from the source after a reflection off the top flange.

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TABLE I. Typical parameters[a] of the various methods of producing neutral beams. For these neutral beam sources to be useful to the semiconductor industry, one must be able to produce high fluxes, $\geqslant 10^{17}$ cm^{-2} s^{-1}, over large areas, with energies in the range from ~0.5 to ~50 eV. (Higher energies might be desired in a few applications.) In addition, a wide range of chemistries and low contamination levels are needed.

Source	Flux (cm^{-2} s^{-1})	Area (cm^2)	Energy (eV)	Limitations
Effusion	$\leqslant 10^{13}$	1–10	$\leqslant 0.5$	contamination
Gas dynamic (nozzle)	$\leqslant 10^{15}$	1–10	$\leqslant 3$	contamination
Continuous				short source life
Pulsed	$\leqslant 10^{18}$ (peak)	1–10	$\leqslant 5$	pulsed, contamination short source life
Mechanical	$\leqslant 3\times 10^{13}$	~100	$\leqslant 1$	pulsed, contamination short source life
Plasma				
Charge exchange	$\geqslant 10^{14}$	~1000	$\geqslant 100$	low flux for low energy
Photodetachment of negative ions	10^{12}* (s^{-1}) *estimate	~1000	5	limited chemistry
Surface neutralization	10^{14}–10^{18}	~1000	1–25	none known

[a]See Ref. 5.

small portion of the wafer would be exposed, resulting in a ''trenchlike'' structure if ashing occurred.

As a test of the neutral beam source, photoresist-coated Si wafers were ashed under a variety of conditions. The gas mixture and the cathode bias, i.e., the beam energy,[18] were varied in this study. With the collimator in place, run times were 20 min; without the collimator, run times were 10 min. For all runs, the total gas pressure in the source was 2 mTorr. For the data shown in Fig. 2, the Ar to O_2 gas pressure ratio was 1 to 1. For the data shown in Fig. 3, the cathode bias was -40 V. Approximately 250 W of deposited microwave power was used to produce and sustain the plasma. The microwave tuning was set so as to maximize the cathode current. (The tuning changed very little from run to run.) The magnetic coil current was 100 A, producing a maximum magnetic field strength of 2200 G on the cathode surface. After ashing, the uncovered areas had uniform glossy appearances, which were distinct from the covered areas.

Measured ash rates are shown in Figs. 2 and 3. These ash rates were determined from the ''trench'' depths and the run time. The trench depths were measured at three or four randomly selected locations at the edge of the exposed surface using a profilometer. While nonuniformities in both the initial surface profile of the photoresist and the spatial profile of the neutral beam results in large scatter in the data, the general trends are still evident.

It is seen that the ash rate increases with the cathode bias (hence the beam energy) and the beam flux (without the collimator). In Si-etching systems, the etch rate increases approximately linearly with the energy flux.[23] Here, the ash rate does not increase linearly with the cathode bias. Possible explanations are: (1) the fraction of energy a hyperthermal neutral loses with each surface collision depends on the incident energy; (2) as the initial energy increases, hyperthermal neutrals undergoing three or more bounces will begin to play a role in the ash process. Also a nonlinearity is observed with respect to the collimator-hole area to tube-area ratio. Here one must consider the flux of hyperthermal neutrals which undergo a third bounce in the collimator/tube prior to reaching the substrate. It is quite clear that the closer a third bounce is to the target, the lower the chance for a fourth bounce, etc.

While the energy distribution of the hyperthermal neutrals is as yet unknown, it can be estimated from the data of Cuthbertson *et al.*[18] The ions will strike the cathode at an energy of $e(V_p+V_c)$, where $V_p \approx 15$ V is the plasma poten-

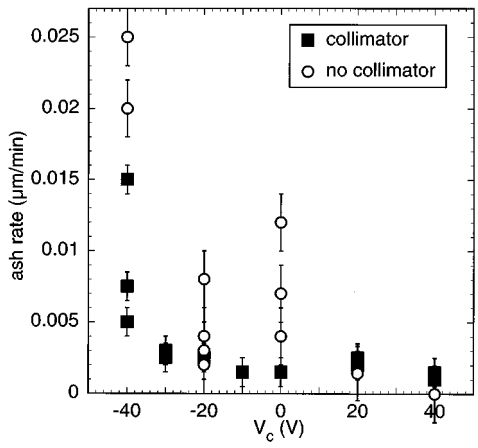

FIG. 2. Ash rate as a function of cathode bias, with and without the collimator in place. For these data, the Ar to O_2 pressure ratio was 1 to 1.

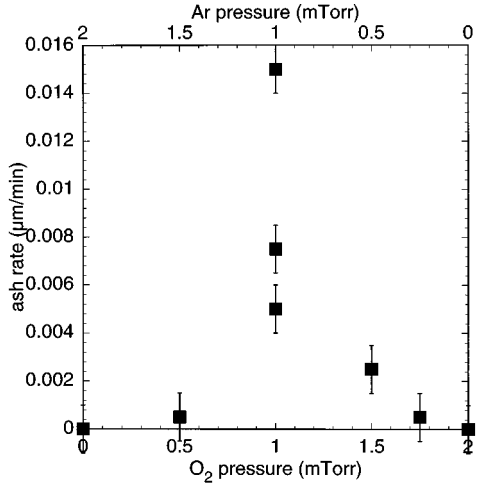

FIG. 3. Ash rate as a function of gas mixture. For these data, $V_c = -40$ V.

tial. For a single bounce, Cuthbertson found the neutral energy distribution was approximately Gaussian, with a peak at $\sim e(V_p+V_c)/2$ and full width at half maximum of ~ 10 eV. This distribution depends on the gas and surface species, as well as incident angles and energies. (It was also found that the binary-collision model is inappropriate at these energies.) Additional bounces will further shift this distribution toward zero. For the maximum bias used here, this gives energies up to ~ 55 eV with the distribution peaked near 10–15 eV. Direct measurement of the hyperthermal neutral energy distributions have not been completed but such work has begun.

The neutral beam flux can be estimated from the ash rate or from geometry. Assuming that each neutral removes one surface atom, we find a flux of $\sim 10^{15}$ cm^{-2} s^{-1}, or an equivalent platen current of ~ 35 mA. To estimate the flux from geometry, we first must consider the flux of ions to the cathode surface,

$$\Gamma_i(\mathbf{r}) = 0.6 n_e(\mathbf{r}) \sqrt{T_e(\mathbf{r})/M} = 0.6 \; n_e c_s . \tag{1}$$

Here n_e is the electron density, T_e is the electron temperature, $\mathbf{r}$ is the position on the cathode, M is the ion mass, and c_s is the ion acoustic velocity. Upon striking that surface, they are neutralized and reflected. The flux of neutrals traveling directly from the cathode to a second surface is

$$\Gamma_i(\mathbf{r}') = A_n \int \cos^n(\mathbf{r},\mathbf{r}') \Gamma_i(\mathbf{r}) d\mathbf{r}, \tag{2}$$

where $\mathbf{r}'$ is the position on that surface, $(\mathbf{r},\mathbf{r}')$ is the angle between the cathode surface normal and the line from $\mathbf{r}$ to $\mathbf{r}'$, and $A_n \cos^n()$ is the normalized scattering profile. Part of these neutrals then travel directly to the platen. The integrated flux to the platen of those neutrals which have made only two bounces is

$$\begin{aligned} \int \Gamma_t(\mathbf{r}'') d\mathbf{r}'' &= A_n^2 \int \int \int [\cos^n(\mathbf{r}',\mathbf{r}'') \\ &\quad \times (\cos^n(\mathbf{r},\mathbf{r}') \Gamma_i(\mathbf{r}) d\mathbf{r})] d\mathbf{r}' d\mathbf{r}'' \\ &\approx g \int \Gamma_i(\mathbf{r}) d\mathbf{r} = 0.6 g \int n_e c_s d\mathbf{r} = g I_c / e, \end{aligned} \tag{3}$$

where $\mathbf{r}''$ and Γ_t are the position and flux on the target, g is a geometric factor, e is the electron charge, and I_c is the cathode current. Similar calculations can be made for those hyperthermal atoms which have made more than two bounces. Assuming $n=1$ and a unform flux to the cathode, we find for our system $g \approx 0.021$. Cathode currents have been measured up to 0.35 A and depend on the tuning of the microwave cavity. Thus the neutral beam source produces equivalent wafer currents of up to 7 mA, corresponding to an average flux of 2×10^{14} cm^{-2} s^{-1}, a factor of 5 below that obtained from the assumption of unity ash rates.

From the model, it is seen that the neutral beam flux can be increased by either increasing the plasma density or changing the chamber geometry. The plasma density is limited[22] to 7×10^{10} cm^{-3}, corresponding to the cathode current of 0.35 A. Higher densities, $\sim 7\times 10^{12}$ cm^{-3}, are expected if the microwave source is reconfigured. Calculations[24] of some new geometries have yielded higher throughput, $g \approx 0.16$. Assuming both higher plasma density and higher neutral throughput indicate fluxes of 10^{18} cm^{-2} s^{-1} and ash rates greater than 1 μm/min are possible, which are required for such a source to be economically[23] useful.

Finally, it is not understood why the gas mixture in Fig. 3 was required to produce ashing. From Cuthbertson's data, one might assume that for the pure oxygen discharge, hyperthermal atomic oxygen should reach the photoresist, resulting in ashing. We have, as yet, not been able to ash photoresist with a pure oxygen beam.

We have shown that hyperthermal neutral beams formed through multiple bounces of plasma ions are feasible. A simple model indicates that beam fluxes which are three to four orders of magnitude larger are possible. Because of the nature of the source, such fluxes can be achieved over large areas. A neutral-beam source having such capabilities far exceeds any currently available. Further studies of the prototype source are planned.

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