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Plasma Processing for Integrated Circuits

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The steady advance of integrated circuit technology is one of the most remarkable technology trends in this era of technological revolution. For example, the 64-k memory chips of the early 1980s are now being replaced by 4-M and even 16-M chips. This trend is expected to continue with chips at the giga-bit level being available in a decade. The needs for ultraviolet and then X-ray lithography to define the submicron features needed for these larger, denser chips have been widely discussed. However, in parallel, the equipment (referred to as tools in the industry) and related processes to carry out the deposition and etching steps needed to actually produce devices in the tenth-micron range also require significant development.

This paper summarizes present and anticipated contributions of magnetic fusion plasma theory and diagnostics and plasma production technology at Oak Ridge National Laboratory (ORNL) for the development of integrated circuit production technology. The discussion is introduced with a review of past technology evolution and of the present economic context for manufacturing.

Introduction

The earliest integrated circuits were fabricated with wet, printed circuit like processes. This type of process was isotropic because etching, for example, proceeded laterally as rapidly as downward and was well-suited for wide, shallow features. Anisotropic processes were needed when the characteristic width of a feature became comparable to or less than its depth (or height). This need led to the widespread introduction of plasma-based processes. The directionality of ions leaving a plasma sheath was used to push processes toward the needed anisotropy. The plasmas were produced by the application of an rf voltage to parallel plates in an "rf diode." Although the processes involved a plasma, the ions, for the most part, acted to control the directionality of a process that was dominated by free radicals produced in the plasma.

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Parallel plate technology has undergone significant improvement and is still by far the dominant plasma technology used in present-day production. Typical plasma densities are in the range of 10^9 to 10^{10} cm^{-3}, with electron energies of a few electron volts. For these parameters, the plasma sheath thickness ranges from several millimeters to 1-cm, and the sheath thickness is comparable to the gap between the electrodes. This is substantially different than a fusion plasma where sheath thicknesses are much smaller than the plasma dimensions. As a result, in part, the connections between fusion physics and technology and plasma process technology were not significant, and the disciplines for the most part evolved independently.

As device dimensions continue to shrink, parallel plate tool limitations are becoming significant. The need for increased anisotropy is pushing the operating regime to lower pressures (tens as opposed to hundreds of millitorr) where ion-neutral scattering is reduced. Diode plasmas are more difficult to operate in this regime and have higher ion energies. At the same time, the damage produced by higher ion energies is becoming more significant because devices with smaller lateral dimensions also tend to be thinner and more susceptible to damage. The result is the need for plasma sources that can operate in the range of a few to tens of millitorr with ion energies as low as a few tens of volts. The need to keep process rates high requires a concomitant increase in ion current density. Thus, the sources must produce plasma densities of 10^{11} to 10^{12} cm^{-3}. The net effect is to bring plasma characteristics into the fusion range where sheath dimensions are much smaller than the plasma size.

The above discussion is in terms of the technical requirements for future process tools. Just as important is the economics of using these tools in a production line. The semiconductor business is global and highly competitive. A few percent difference in the cost of ownership of a tool or in its impact on device yield is very often the difference between profit and loss for a plant with capital cost approaching a billion dollars. Thus, in the following discussion of physics and technology, remember that while performance is often the focus of early development, in the long term it is not dominant; simplicity, reliability, and robustness are as likely to determine the success or failure of a development effort.

The remainder of this paper briefly summarizes two examples of ORNL projects that are contributing to the development of process technology for integrated circuit manufacture. These include modeling of radio frequency induction (RFI) plasma sources [under a program managed by Sandia National Laboratories (SNL) and sponsored by the

Department of Energy (DOE) and SEMATECH] and the development of advanced metallization technology [a cooperative research and development "activity" (CRADA) between ORNL and International Business Machines, Inc. (IBM), sponsored by DOE]. In addition, projects in plasma cleaning, microwave window development, and plasma diagnostics are now under negotiation. The references in this article are schematic at best, and the reader is referred to the excellent review in the chapter on the design of high-density plasma sources for materials processing in Physics of Thin Films (Academic Press, 1993) by M. A. Lieberman and R. A. Gottscho for a more complete set.

Plasma Modeling

The RFI high-density plasma source is being used by several domestic tool vendors as the basis for their next generation of process tools. A coil, either cylindrical or planar, is driven by an rf power source in the megahertz frequency range to induce an rf current in the plasma. The planar coil is a spiral and shaped much like the element of an electric range. This plasma source is relatively simple and does not require an external magnetic field as do sources based on the electron cyclotron resonance (ECR) interaction or on helicon waves.

The development of process tools has historically been dominated by an empirical approach. If predictive models could be developed, the time and cost of this development could be reduced, and a better tool could be introduced into the market earlier with reduced cost, thus improving the industry's competitive position. For these reasons, SEMATECH and the DOE are developing a plasma modeling capability for RFI plasma sources.

An important component of an overall plasma simulation model is the computation of rf fields and currents and the resultant power deposition. As part of a larger program under SNL, ORNL is applying the understanding it has gained from fusion rf heating development to RFI plasma sources to develop a computational model for RFI power deposition . For sufficiently high operating pressures, approximately 5 to 10 millitorr, the heating is ohmic, with the electron collision frequency being dominated by neutral collisions. [J. Hopwood et al., J. Vac. Sci. Technol. A 11, 152 (1993).] The calculation of the induced plasma current is relatively straightforward, and the power deposition follows immediately from the plasma conductivity. The current in the rf coil is constant, and the problem is similar in concept to that of an rf transformer with the plasma forming the secondary.

However, currents and fields also result from capacitive coupling between the rf coil and the plasma. (Inductive fields result from changing currents, while capacitive fields are electrostatic in nature.) Under these conditions, the current along the rf coil is no longer constant; much like the classical antenna problem, the current in the coil must be calculated self-consistently. The results from one such calculation are shown in Fig. 1 for a cylindrical RFI plasma with a planar coil. The small rectangular objects represent the four turns in the rf coil, and the larger solid indicates the location of a dielectric window, usually quartz or alumina, which also forms a vacuum barrier. The inside coil is driven at about 1 kV, while the outside turn is near ground potential. The contours indicate the location of constant power deposition surfaces. As a result of the capacitive coupling, the outermost contour is distorted and indicates increased power deposition under the high-voltage end of the coil. This power deposition model is now being used by collaborators at SNL and the University of California, Berkeley, as input to their plasma transport simulations.

Advanced Metallization

Once the devices on an integrated circuit have been produced, they must be hooked together into a functioning system. Much like a multilayer printed circuit board, several layers of interconnects must be employed. In practice, in part due to the resistance of the aluminum "wires," the number and therefore the complexity and cost of layers is increasing as the feature size shrinks. One approach to reducing the number of layers is to use a higher conductivity material, namely copper, for the interconnections.

However, the technology to deposit copper in narrow deep features does not presently exist. While it is possible to heat a silicon wafer to sufficiently high temperatures to allow aluminum to flow into the high aspect ratio holes and trenches that form the interconnections, the temperatures needed for copper are too high. In addition, there is a desire to replace the inorganic insulators used in present circuits with lower dielectric constant organic materials such as polyimide to reduce the RC delay times that can limit a circuit's speed. These organic materials will reduce the maximum acceptable process temperatures, making the reflow of even aluminum problematical.

To address this problem, W. M. Holber and colleagues at IBM's Watson Research Center, developed an ECR plasma source that was fed by a metal vapor. [W. M. Holber et al., J. Vac. Sci. Technol. A 11, (Nov-Dec 1993).] The metal ions produced in this source were successfully used to fill high aspect ratio features with copper at temperatures < 300° C. The technology used in this source, however, did not lead to a commercial tool. One complexity was the large circular electromagnetic coils used to produce the magnetic fields needed to resonant with 2.45-GHz microwave power. Independently, T. D. Mantei, at the

University of Cincinnati, had developed a permanent magnet electron cyclotron heating (ECH) source. [T. D. Mantei and S. Dhole, J. Vac. Sci. Technol B 9, 26 (1991).] However, this source used a microwave window that was exposed to the ECR plasma. This window, if used with a metal plasma, would have rapidly become coated with the metal and would no longer transmit microwaves.

As part of its CRADA with IBM, ORNL has built on the work described previously and developed a permanent magnet ECR source with a remote microwave window that has operated successfully for extended periods of time in the presence of a metal ion plasma. Similar to that used in fusion neutral beam ion sources, this source is used to feed a magnetic multipole bucket that produces the needed plasma uniformity. The plasma produced by this source is shown in Fig. 2.

To process silicon test wafers, the plasma source described previously has been integrated with a test platform that includes load-locked wafer handling. This platform (shown in Figure 3) was used in a SEMATECH project to develop ECR-based silicon etching technology.

This project, done in collaboration with the Solid State Division, draws on both the fusion and nonfusion expertise of ORNL. This multidisciplinary approach is typical of semiconductor-related projects at ORNL.

Summary

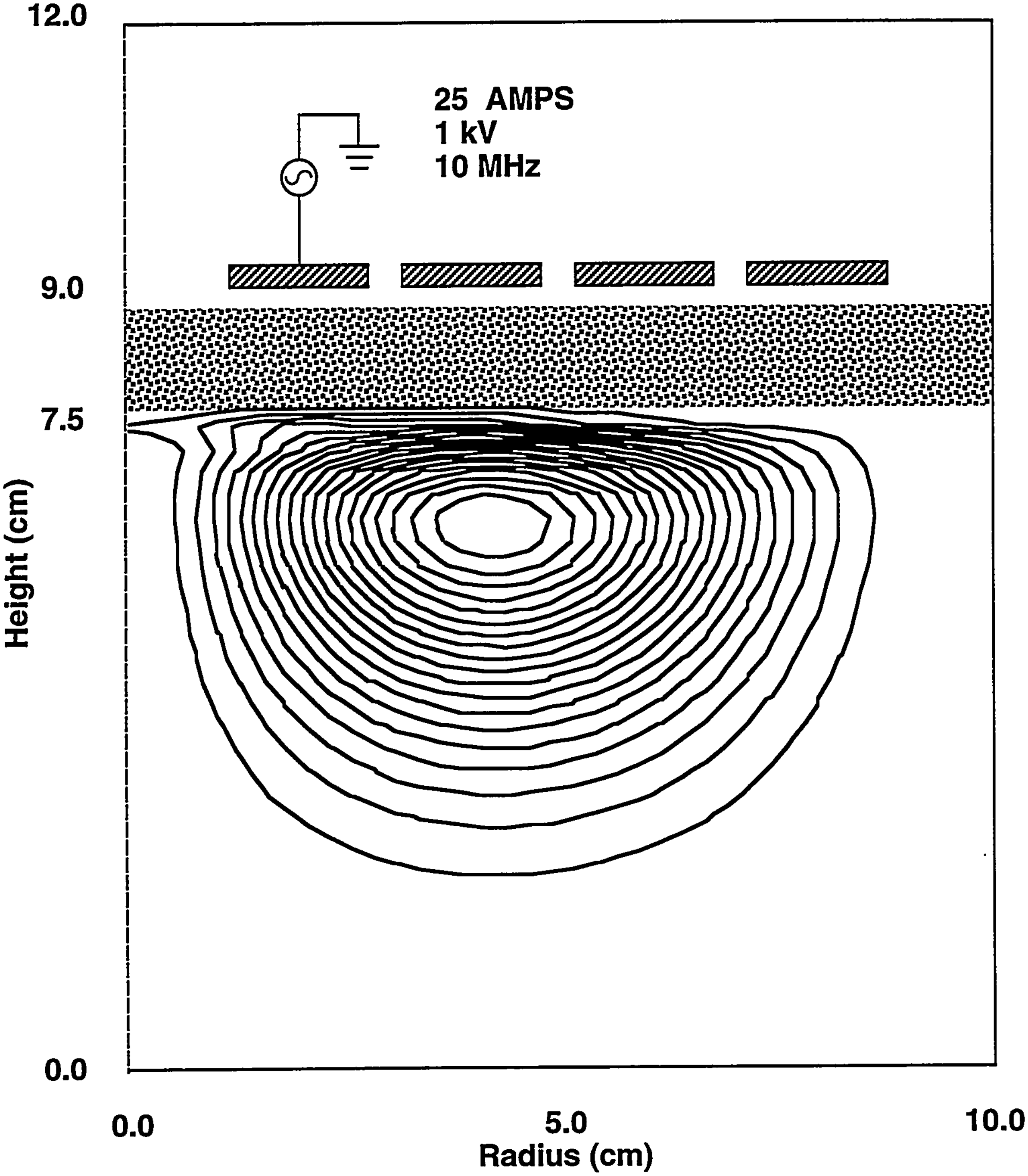
The physics and technology developed in the Magnetic Fusion Program is now being applied to the development of process equipment for the semiconductor industry. At present, a number of projects are under way at ORNL and other fusion laboratories. These projects are advancing technically and contributing to the advances needed to fabricate future generations of large-scale integrated circuits. The judgment of the value of these contributions awaits the real tests of production and commercial impact.

Figure Captions

Fig. 1 Contours of constant power deposition for planar coil RFI

Fig. 2 Plasma emmision for permanent magnet ECR feeding magnetic multipole magnetic bucket.

Fig. 3 The SEMATECH ECR etch facility.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