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Helicon plasma source for ionized physical vapor deposition

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Abstract

A helicon antenna that sits remotely outside the vacuum system is attached to a magnetron sputtering system. This increases the electron temperature, which increases the ionization of the sputter flux for achieving ionized physical vapor deposition (IPVD). There are no shadowing and contamination problems, unlike other IPVD devices with immersed coils, since the helicon antenna is outside the vacuum system. Furthermore, the target to substrate distance can be kept small. At 2 kW magnetron power, 4 kW helicon power, 45 mTorr argon gas, and with a copper target, ionization fractions to the substrate of 51 ± 10% and a deposition rate of 847 ± 42 Å/min are measured using a quartz crystal oscillator (QCO) and a multi-grid filter. Without the antenna, the ionization fraction to the QCO is 30 ± 6% and the deposition rate is 815 ± 41 Å/min. Multiple remote sources are envisioned to be positioned radially around a sputtering chamber, controlling uniformity while increasing the ionization further. Since 21% additional ionization is achieved using only one source, with no threat of contamination inside the vacuum chamber, the helicon source has good potential for a secondary plasma source in IPVD applications.

Keywords: Helicon antenna; Ionized PVD (IPVD); Magnetron sputtering; Plasma source

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1. Introduction

Increasingly narrow features are required as semiconductor technology advances. It is more difficult to deposit barriers, liners, and seed layers into these features due to the ‘pinch-off’ or ‘bread-loafing’ effect, which leads to voids [1]. For copper deposition, electroplating is a likely technology for filling the majority of a feature, however, a seed layer is still required. Chemical vapor deposition (CVD) and ionized physical vapor deposition (IPVD) [1] are possible technologies for liners and seed layers. Since CVD has not been successfully realized on a commercial scale for copper, and IPVD has started to have commercial success, improvements in IPVD should enable the technology to be extended to future generations of feature size. Most IPVD research has been done using immersed inductively coupled plasma (ICP) coils [2–9], although there has been some work using other plasma sources for ionizing the metal, such as microwaves [10] and external ICP coils [11].

Immersed ICP coils have problems with flaking, contamination, self-sputtering, and shadowing [12]. A new remote secondary plasma source is designed to increase the electron density and temperature in a sputtering chamber without protruding into the line-of-sight from the target to substrate, or even into the deposition system. In addition there is no need to extend the target to substrate distance to make room for internal coils. The additional plasma ionizes the metal sputter flux, resulting in the IPVD effect for better deposition in high-aspect ratio (AR) trenches and vias. The remote source is an attached helicon antenna, which sits outside the vacuum chamber but launches plasma from a cylindrical tube into the magnetron discharge. A patent application has been filed on possible commercial applications for this device.

Helicon antennas are known for their remarkable efficiency and ability to achieve high-density plasmas. Early work with the Nagoya type III antenna, shown in Fig. 1, achieved electron densities up to $10^{14}\,\mathrm{cm}^{-3}$. Chen and Boswell’s review paper [13] is recommended for a complete and recent explanation of the efficiency of helicon antennas at producing high-density plasmas.

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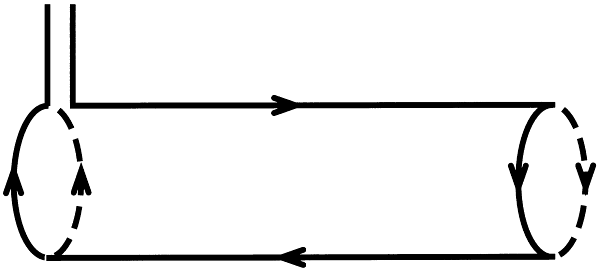

Fig. 1. A picture of the Nagoya type III antenna.

2. Experiment and results

A 33 cm copper target rotating magnetron [the Materials Research Corporation (now Tokyo Electron Arizona, Inc.) Galaxy machine] for processing 200 mm wafers is modified with an attached quartz tube on the side of the chamber. As seen in Fig. 2, a helicon antenna (Nagoya type III) is placed around the tube, and a variable electromagnetic coil is placed around the antenna. The B-field profile of the 30 cm long magnetic coil is graphed in Fig. 3 for various currents. A Henri Radio 13.56 MHz 10 kW power supply with a built in tunable dual-capacitor π-matching network is used.

A diagnostic consisting of a quartz crystal oscillator (QCO) and a multi-grid filter used for measuring the deposition rates and the ionization fractions is shown in Fig. 4. The calibration methods and details of this diagnostic are outlined in Ref. [15]. The QCO, three grids, and substrate are typically biased at −30 V to attract the ions across the sheath. With this arrangement the total deposition is measured. With the bottom grid biased at a positive voltage above the plasma potential, the ions are screened out and the neutral deposition is read. This voltage, +40 V in these experiments, is determined by incrementally increasing the bottom grid voltage until the deposition flattens off. Two grids are necessary above it to effectively screen out the plasma electrons. The diagnostic is embedded in the substrate plane, a distance of 140 mm from the target.

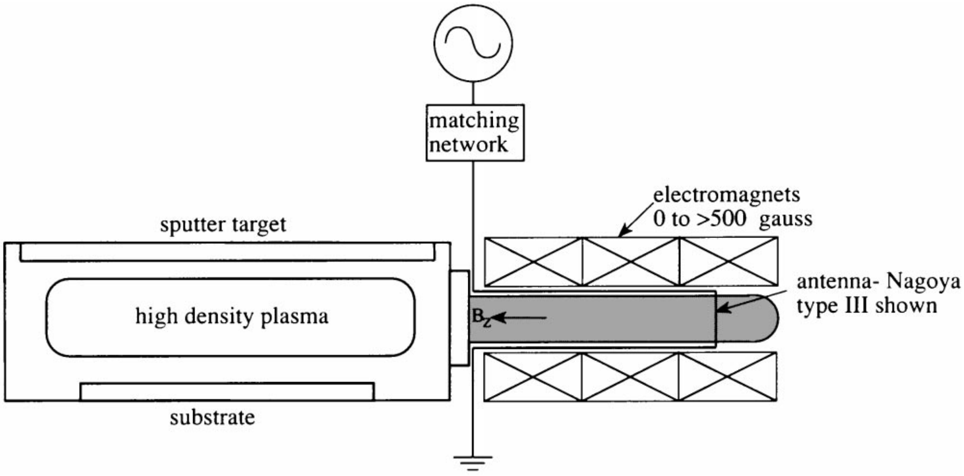

Fig. 2. A side-view of the helicon device attached to the magnetron sputtering chamber.

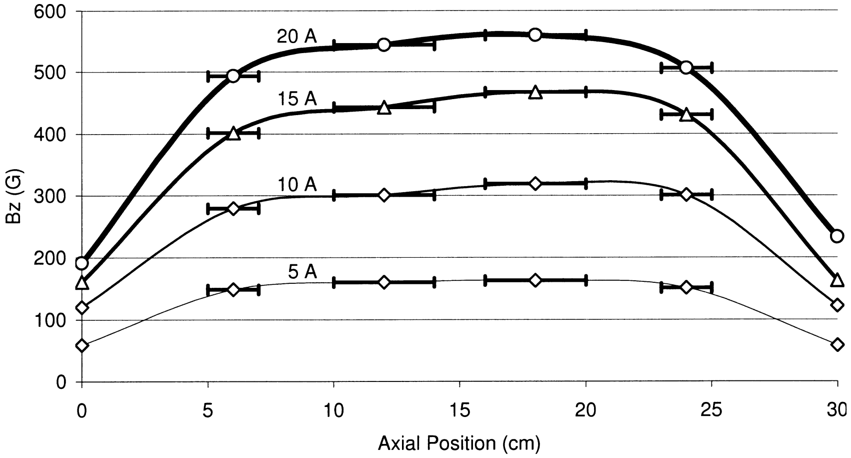

Fig. 3. The magnetic field profile of the coil in Fig. 2. The gaussmeter is moved along the center axis for the length of the coil (beginning of coil at 0 cm, end of coil at 30 cm).

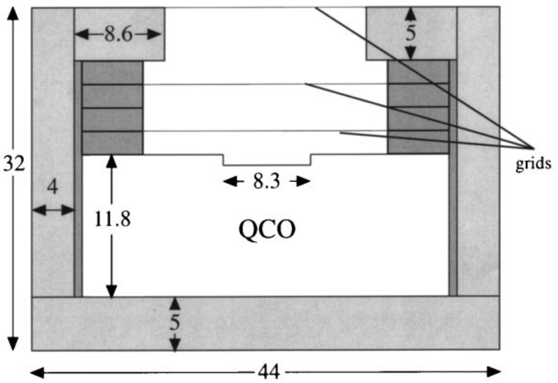

Fig. 4. The sensor consists of a quartz crystal oscillator (to measure the deposition rate) and a gridded ion and electron filter. The dimensions are given in millimeters.

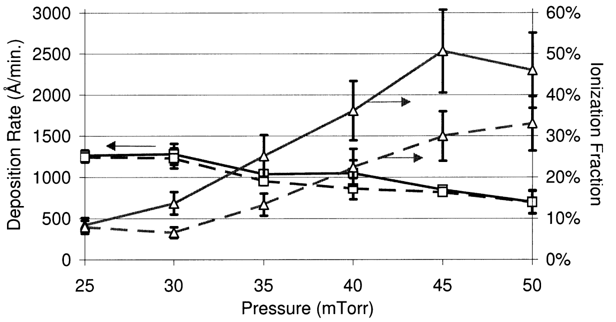

Fig. 5. Deposition rates and ionization fractions vs. pressure for 4 kW helicon antenna at 2 kW magnetron power. For comparison, data is also plotted for the same conditions with no helicon power (dotted lines).

Experiments are run at six pressures (argon background gas at 25 to 50 mTorr) and three magnetron powers (2, 3, and 4 kW). The helicon antenna is typically run at 4 kW, but data is also taken at zero helicon power to illustrate the effectiveness of the helicon, and probe data is collected at several powers. The data collected is the deposition rate to the substrate and the ionization fraction to the QCO. It is possible to deduce the ionization fraction to the substrate (described in Ref. [12]) but the fractions delivered to the bottom of the QCO are more representative of what would be deposited at the bottom of a 1:1 AR via. The 3 and 4 kW cases showed very small increases in ionization with the helicon antenna, likely due to the increased copper flux cooling the plasma and rarefying the argon as explained in Ref. [6]. However, substantial increases are found at 2 kW, as seen in Fig. 5.

Table 1
Electron temperatures and densities, and plasma potential, for various RF powers at 35 mTorr and 2 kW magnetron power

RF power (kW)	T_e (eV)	n_e (cm^{-3})
0	0.92 ± 0.10	$1.7 \pm 0.8 \times 10^{10}$
2	1.4 ± 0.2	$1.4 \pm 0.8 \times 10^{10}$
4	1.8 ± 0.1	$1.4 \pm 0.8 \times 10^{10}$

One potential problem is that metal is depositing, and at higher pressures it scatters more and could coat the inside of the quartz tube, affecting the antenna's efficiency. To prevent this, glass tubes could be placed inside the quartz tube which would prevent the coating from occurring too far into the device. Four 13 mm diameter tubes are placed inside as shown in Fig. 6, and this is tested to see if the physical presence of the extra tubes changes the performance of the system. The ionization fraction is measured with the four tubes at 35 mTorr, 2 kW of magnetron power, and 4 kW of helicon power. The ionization fraction to the QCO is determined to be 25.0 ± 5% with the tubes vs. 25.1 ± 5%, virtually identical within error.

Plasma parameters were measured with an RF compensated Langmuir probe apparatus. The probe is RF compensated [15] in order to yield accurate measurements in the RF environment. Because exposed surfaces in the chamber are continuously coated by sputtered copper atoms, precautions must be taken to prevent the probe tip from shorting to the rest of the probe by enclosing it in a hollow sheath [16]. A similar sheathing technique is used to protect the compensation electrode from shorting to the probe body. The probe tip was placed horizontally in the center of the chamber, perpendicular to the line of sight from the helicon tube and about 165 cm from the junction of the tube with the chamber wall.

For a typical probe *I–V* trace, the voltage on the probe tip was swept through 150 V, from 120 V below plasma potential to 30 V above. This sweep occurred in 0.1 s, and was repeated 25 times, with consecutive sweeps 1 s apart. The results of these sweeps were averaged to reduce noise and then analyzed to yield plasma parameters [17]. This procedure was performed at several

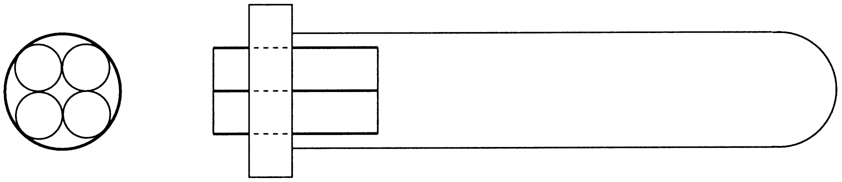

Fig. 6. A schematic of the quartz tube with four smaller tubes placed inside to prevent coating near the antenna. Side cross-section and end views are shown.

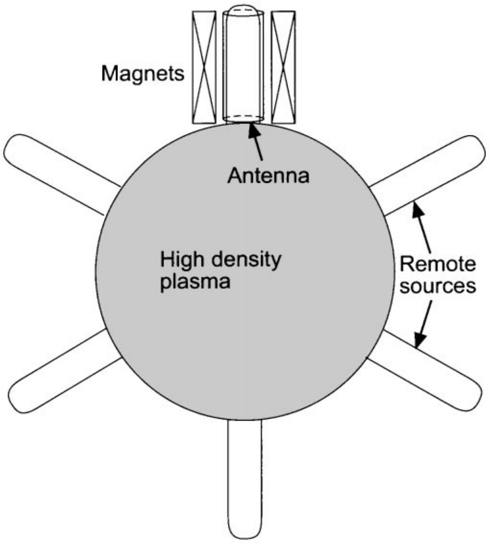

Fig. 7. A top view of the conceptual helicon IPVD system.

widely separated times in order to ensure repeatable results.

As can be seen in Table 1, the addition of RF power from the helicon antenna significantly raises the electron temperature while leaving the density unchanged within the accuracy of the measurement. These results are consistent with the increased ionization seen as the antenna power is increased. The ionization rate is proportional to the density (which does not change) but more than proportional to the temperature (which doubles when 4 kW of RF power is applied).

3. Conclusion and comments

A new IPVD source utilizing a remote helicon antenna as the secondary plasma source is shown to increase the electron temperature and increase the ionization of the depositing flux. The addition of more helicon sources could substantially increase the difference too, by uniformly increasing the temperature and density much higher than the one source alone. A conceptual design showing the top view of a magnetron chamber with six helicon sources attached is shown in Fig. 7. The magnets and antenna would be attached to each quartz tube, but they are only shown for one. Although this idea has not been demonstrated, it is envisioned that a helicon commercial IPVD system would have multiple sources such as in Fig. 7, with even 10 or 12 depending on the size of the wafer. The target to substrate distance could be decreased compared to other IPVD systems, thereby increasing the sputtering rate. The remote location of multiple antennas removes the threat of contamination or flaking from any coil sputtering, and maintenance of the antenna can be done outside the vacuum system. This new device can potentially be used for future IPVD applications.

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