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Unbalanced dc magnetrons as sources of high ion fluxes

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We report the characteristics of a new design of magnetron sputter source (a UM-gun), based on the principle of an unbalanced magnetic design, and capable of giving ion fluxes at the substrate greater than the flux of depositing atoms. The dependencies of ion flux and self-bias potential at a typical substrate position for certain target materials (copper and silicon), gas pressures (0.25–5 Pa), gas compositions (Ar with O_2, N_2, and He), and sputtering power levels (up to 2 kW) have been measured for a particular UM-gun. The results show that such guns can be characterized approximately by an ion flux proportional to the discharge current and a constant self-bias potential.

I. INTRODUCTION

Magnetron sputtering has become widely used in both research and production since its development more than a decade ago.[1–4] In conventional magnetrons, the discharge is confined by the magnetic field close to the cathode surface, and consequently the bombardment of the growing film by energetic particles (other than the depositing atoms) is minimal.

However, there are many situations where the properties of the thin film are improved by bombarding the growing film with energetic ions.[5–8] Effects of ion bombardment during deposition include making the film more dense and preferentially orienting the crystallites in the deposit. The available technology for ion assisted deposition, particularly where separate sources are used for the deposition flux and the ion flux, is difficult to implement in many production situations. The ability to provide a controllable ion flux from a planar magnetron while retaining the many other desirable features (simplicity, high deposition rate, geometric versatility, toleration of reactive gases) would assist in the implementation of ion beam assisted deposition in both research and production.

We have developed a new type of planar deposition source, which gives the normal deposition behavior of a planar magnetron, plus a beam of ions whose intensity at the substrate can be varied independently of the deposition flux by changing the magnetic field configuration. A detailed study of the axial and radial dependencies of the ion flux and the self-bias voltage for various magnetic field configurations has been presented elsewhere.[9] We report here the dependencies of ion flux and self-bias voltage on the discharge current, gas pressure, target composition, and gas composition. The results show that the ion flux is proportional to the discharge current, is independent of target composition, and is approximatley independent of the gas pressure and gas composition. In addition, the self-bias voltage is approximately constant over the same range of conditions.

The ion flux produced by these sources is a direct result of the unbalanced magnetic arrangement in the magnetron and we propose the name UM-gun for such sources. They can provide large fluxes of ions whose energies can be varied upwards from a few eV, spanning an energy range which is difficult to cover with conventional ion beam guns. We foresee many applications in ion assisted deposition, at both the research level for small UM-guns, and at the production level for very large UM-guns.

II. EXPERIMENTAL DETAILS

The UM-gun and a probe assembly similar to that described in our earlier paper[9] are shown in Fig. 1. The magnetron uses a permanent magnet assembly of the unbalanced type, comprising an outer annular permanent magnet (Alnico V with outer diameter 70 mm and inner diameter 37.5 mm) and an inner soft iron pole (10 mm diam). The probe, in the form of an 8 mm diam disk, is mounted in front of a 100 mm diam backing disk, so that its behavior is that of a small region in the middle of a large substrate. Both the probe and the backing disk are floated when the self-bias potential is determined, and both are biased at -100 V when the ion current to the probe is measured.

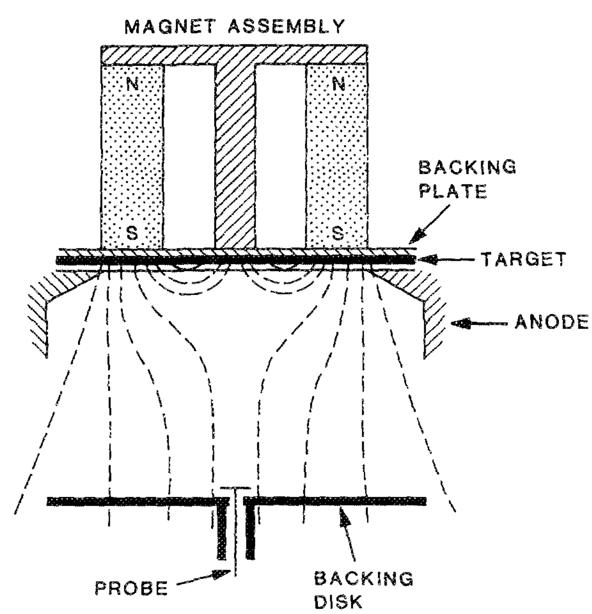

FIG. 1. Magnetron and probe assembly are shown schematically. For the measurements reported here the target to probe distance was maintained at 60 mm.

III. RESULTS

The self-bias potential V_{sb} with respect to the anode, and the probe current I_b under $-$ 100 V bias with respect to the anode were measured under a range of sputtering conditions. Figure 2 shows the results for V_{sb} and I_b obtained with silicon or copper targets, using argon gas at 1 Pa pressure, as functions of the discharge current. Figure 3 shows V_{sb} and I_b as functions of the argon gas pressure at a fixed discharge current of 300 mA. Figure 4 shows V_{sb} and I_b versus the mole fraction of argon in the sputter gas (total pressure 1 Pa) at a discharge current of 300 mA.

IV. DISCUSSION

The operation of the UM-gun as a sputter source, and the role of the unbalanced magnetic field have been discussed in detail elsewhere.[9] Briefly, the important feature is the directing of the electrons towards the substrate by the magnetic field pattern. This gives an increase in the ion bombardment of the substrate, both because more ions are created near the substrates, and because ions must move with the electrons to maintain the electrical neutrality of the plasma.

The origins of the quantities V_{sb} and I_b shown in Figs. 2–4 are well known.[10,11] In general, a probe placed in a plasma will be bombarded by a much higher flux of electrons than ions, and an isolated probe will charge negatively with respect to the plasma until the fluxes are equal. This is the self-bias potential of the probe or substrates with respect to the plasma and insulating or insulated substrates will adopt this potential. The current I_b to conducting substrates measured at $-$ 100 V bias is predominantly due to ions diffusing to the probe, and is approximately independent of probe potential (we ignore the small effect of secondary electron emission).

Ions reaching the substrate have energies proportional to the potential of the substrate surface with respect to the plasma. The application of bias voltages and the measurement of self-bias voltages are more easily made with respect to the

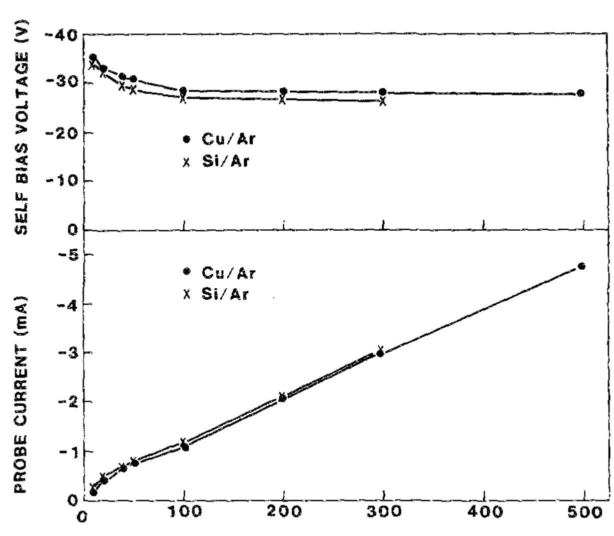

FIG. 2. Current when biased at $-$ 100 V and the self-bias voltage of an on-axis probe of 8 mm diam spaced 60 mm away from the magnetron sputter source are shown as functions of the actual cathode current for copper and silicon targets and 1 Pa of argon.

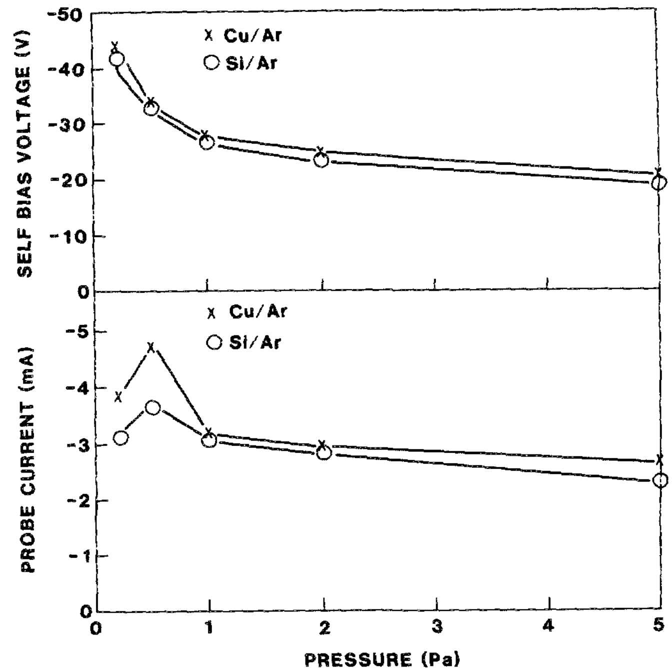

FIG. 3. Current when biased at $-$ 100 V and the self-bias voltage of an on-axis probe of 8 mm diam spaced 60 mm away from the magnetron sputter source with silicon or copper targets and a cathode current of 300 mA are shown as functions of argon gas pressure.

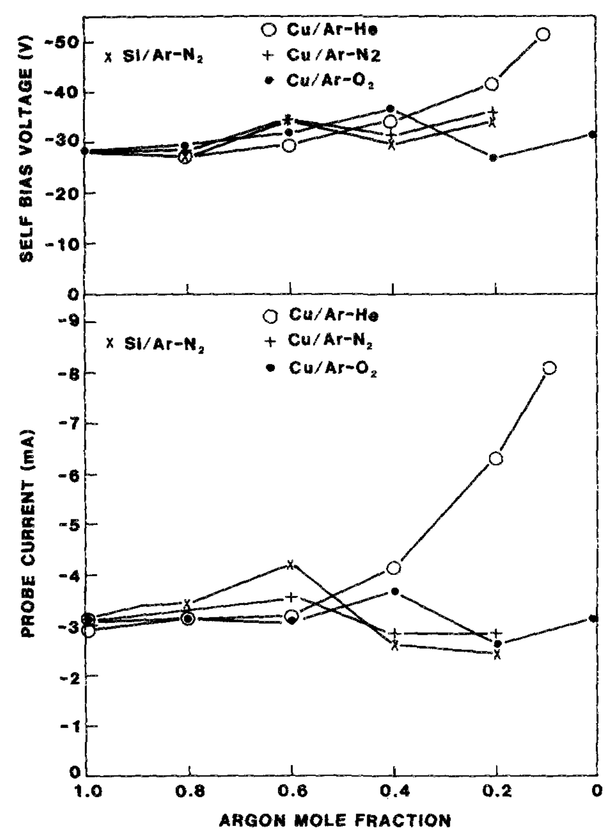

FIG. 4. Current when biased at $-$ 100 V and the self-bias voltage of an on-axis probe of 8 mm diam spaced 60 mm away from the magnetron sputter source with silicon or copper targets and a cathode current of 300 mA are shown as functions of the argon concentration in the gas. The pressure was maintained at 1 Pa.

anode, and a knowledge of the plasma potential is required to obtain the full ion energy. We have made some measurements of the plasma potential using probes, and have found values close to + 2 V at pressures of 1 Pa. This is comparable with other reported values of 2–10 V,[12] and consistent with the effective containment of the electrons in the plasma by the magnetic field arrangement, i.e., large electric fields are not required to inhibit electrons from reaching the anode.

The major features of the data shown in Figs. 2–4 are that the self-bias voltage changes little with changes in the discharge conditions, and that the probe ion current depends linearly on the cathode discharge current and is approximately independent of other factors such as gas pressure and gas and target composition. This behavior can be understood in terms of the essential physics of magnetron discharges.

The ionization in the plasma is sustained by secondary electrons released during sputtering of the cathode, dissipating in the body of the plasma the energy they acquire in crossing the cathode sheath. Most of the ionization is produced in the magnetron tunnel or trap, and it is this region which dominates the overall behavior.

The cathode ion current and the probe ion current are determined by the diffusion of ions from the regions where they are created, mainly the magnetron trap, to the surfaces. The physical quantities which affect the trap are the initial energy of the secondary electrons and the properties of the gas, principally the ionization probability (determined by the gas pressure and the total ionization cross section). If the relative profile of the plasma does not change with changing conditions, the ion current as collected by the probe should be a constant fraction of the cathode current.

It is a feature of the magnetron discharge that the operating voltage for a given target and gas combination is only slowly dependent on cathode current and also gas pressure. Thus the energy of the secondary electrons entering the plasma is approximately constant. At a given pressure, the ion current collected by the probe should be directly proportional to the cathode current, as is observed (Fig. 2). As the pressure decreases, the probability of ionization in the plasma decreases, and the ionization will be created further away from the cathode, causing the probe ion current to increase for a constant cathode current (Fig. 3). The self-bias voltage should also increase, as the electrons reaching the probe are more energetic. The cathode voltage does not change appreciably on changing the target from copper to silicon, and the ratio of probe current to cathode current should not change, as is observed.

The behavior with different gases shown in Fig. 4 reveals that, provided the argon concentration is above 50%, the ion current and self-bias voltages are approximately constant. Higher concentrations of oxygen and nitrogen also give similar ion currents and self-bias potentials, but adding helium above the 50% level causes the self-bias potential to rise and the ion current to increase markedly.

The ionization cross section for argon, nitrogen, and oxygen are similar in both magnitude and energy dependence over the range of electron energy from 10 to 500 eV.[13] Thus small changes in ion current and self-bias voltage for constant cathode current will occur as nitrogen or oxygen is added to argon. Helium has a lower ionization cross section than argon by about a factor of 10, and the energy dependencies are similar.[13] The lower ionization cross section for helium produces an increase in the cathode voltage. This increase in the energy of the secondary electrons and the lower cross section result in ionization being created more towards the substrate, i.e., the probe ion current increases for constant cathode current, as is observed. Also since the energies of electrons reaching the substrate are higher, the self-bias voltage increases as helium is added (Fig. 4).

The UM-gun is a simple, reliable, low cost source for ion beam assisted deposition. The one source, powered by a dc power supply, provides not only the flux of depositing atoms but also a flux of ions and a flux of electrons at the substrate. In the case of insulated or insulating substrates, the presence of the electron flux neutralizes the ion flux and allows the substrates to reach significant self-bias voltages (>25 V) with respect to the plasma. In systems with separate ion beam guns, an electron flood system has to be provided to neutralize the ion beam.

For conducting substrates and for conducting or semi-insulating films, the ion energy can be varied by dc biasing the substrates or the depositing films. For insulating substrates and films, rf biasing can be used to vary the ion energy. The plasma potential is approximately + 2 V and thermal ion energies are <5 eV, so that well defined ion energies in the range upwards from a few eV can be achieved. The lowest energies are well below those that can be readily supplied by ion beam sources.

The upper limit to the ion energy is set by resputtering, which becomes particularly pronounced when the cathode and the substrate start to function as the cathodes of a Penning discharge (see Ref. 4). This resputtering has been used to clean conducting substrates.

The magnetic geometry can be achieved and varied in assorted ways. The simplest method uses permanent magnets as described here, but electromagnets can be used to give excellent control over the ion flux independently of the deposition flux.

V. CONCLUSION

We have shown that for the unbalanced magnetrons or UM-guns, the ion fluxes to probes at typical substrate distances are to a good approximation proportional to discharge current, and are independent of pressure and independent of the gas mixture for those cases investigated. In addition, for these same cases the self-bias voltage is approximately constant with discharge current, pressure, and gas composition.

We conclude that once a given UM-gun with a certain magnetic field configuration is characterized in terms of ion flux and self-bias voltage, these figures may be used in subsequent applications where the targets are changed or the gas composition is changed. Of course, in those applications where the ion flux is critical, careful measurements would need to be made.

ACKNOWLEDGMENT

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