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ELECTRON CYCLOTRON RESONANCE MICROWAVE ION SOURCES FOR THIN FILM PROCESSING*

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Abstract

Plasmas created by microwave absorption at the electron cyclotron resonance (ECR) are increasingly used for a variety of plasma processes, including both etching and deposition. ECR sources efficiently couple energy to electrons and use magnetic confinement to maximize the probability of an electron creating an ion or free radical in pressure regimes where the mean free path for ionization is comparable to the ECR source dimensions.

The general operating principles of ECR sources are discussed with special emphasis on their use for thin film etching. Data on source performance during Cl based etching of Si using an ECR system are presented.

I. Introduction

Plasmas created by microwave absorption at the electron cyclotron resonance (ECR) are well suited to a variety of thin film processing applications.[1,2] ECR plasma sources were developed in the 1960s for fusion[3] and thruster[4] applications and were

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adapted in the 1970s for use in thin film processing[5] and ion implantation.[6] Since then, they have been used for deposition of SiO_2,[7] Si_3N_4,[7] Si,[8,9] SiC,[10] GaAs,[11] TaO,[12,13] NbO,[12] Al_2O_3,[13] diamond,[14] and BN.[15] Etching has been demonstrated for Si,[8, 16-19] Mo,[18] GaAs,[20] and other III-V based systems.[21] Doping[22] and taper-etching[23] applications have also been effective. ECR microwave plasma source advantages include operation over a wide pressure range; low intrinsic ion energies (as low as 10–20 eV); high gas efficiency; and electrodeless operation.

II. Source Operating Principles

A. Two Coil Mirror

The key to providing these advantages is a configuration which allows both direct energy absorption by electrons without the need for collisions (as is needed for unmagnetized microwave or radio frequency 13.56 MHz sources[2]) and provides plasma confinement. An example of such a configuration is the two coil mirror,[24] in which current flows through the coils to produce a magnetic field as shown in Fig. 1. Radial confinement occurs due to the tendency for electrons and ions to spiral along field lines when Larmor radii are much less than the characteristic ECR source dimension, although some cross field transport occurs.

Energetic electrons, especially those with high velocities perpendicular to the magnetic field, can be trapped in the magnetic minima due to conservation of energy and magnetic moment. This additional confinement increases the probability of ionization over that provided by radial confinement alone. Only electrons with relatively high axial velocities, usually obtained from collisional scattering, can escape the mirror and electrostatically pull ions out with them.

A resonant cyclotron interaction provides the mechanism for absorption of microwaves by electrons. When microwaves are injected as shown in Fig. 1, they tend to propagate through the plasma until the local electron cyclotron frequency is equal to the microwave frequency. This ocurrs at a field of 87.5 mT for the 2.45 GHz power commonly used in ECR plasma sources. At that field, the microwaves are strongly absorbed by the electrons. In practice resonance broadening due to, for example, the doppler shift in microwave frequency seen by electrons with finite axial velocities, causes absorption to occur over a range of magnetic fields, with the range increasing with electron temperature and plasma density. Absorption takes place at fields as much as 5–7 mT away from resonance for plasma parameters characteristic of ECR sources. Collisional absortion, especially at higher pressures (tens of mTorr), and parametric absortion may also be important in some circumstances.[2]

An important feature of the configuration, shown in Fig. 1, is high field injection, i.e., the presence of a magnetic field at the microwave entrance window which is (1) higher than field required for ECR and (2) parallel to the direction of microwave injection. When these two conditions are met, efficient plasma production can occur even in overdense plasmas where the plasma frequency is much higher than the wave frequency. Without high field injection, the 2.45 GHz microwaves are cut off and cannot propagate through plasma densities higher than ~7×10^{16} m^{-3} (i.e., the density which correponds to a plasma frequency of 2.45 GHz). High field injection is also applicable in single coil (no mirror) ECR configurations.

B. Multipole Configurations

Additional radial confinement and improved plasma uniformity can be obtained by using a multipole bucket below or as an integral part of the primary plasma source as shown in Fig 2.[25] Each cusp of the multipole magnetic field acts like the field maximum in the magnetic mirror and effectively confines a majority of the plasma. If high field permanent magnets, such as samarium cobalt, are used to form the multipole fields, microwave antennas can be placed at the cusps to use the resonant magnetic field there to both create and confine the plasma.[26]

Other ECR source configurations which provide both enhanced plasma production and confinement include those based on tunable microwave cavities. These sources, which often also use a bucket to provide radial confinement and uniformity, have been developed extensively and have been reviewed elsewhere.[27]

C. General Operating Characteristics

Typical operating characteristics of systems currently used for deposition and etching include a microwave frequency of 2.45 GHz, pressures of 0.1–5 mTorr, microwave powers of 100–2000 W, chamber diameters of 0.08–0.1 m (the characteristic of an S-band waveguide) to 0.3–0.4 m. Under these conditions, plasma densities of 10^{17} to 10^{18} m^{-3} [28] with ion energies below 40 eV[29,30] are obtained. Higher pressures tend to be used for deposition.

Uniformity over large (>6" diam) areas is often achieved, regardless of the specific ECR source design, by utilizing a multipole bucket configuration.[31] A measure of the overall source performance is the power required to produce an ampere of useful ion current. This power is in the 200–300 watts per ampere range and is remarkably constant for optimized ECR sources of all types.

III. Etching

A. General Etching Requirements

The importance of ion energy control is perhaps most clearly illustrated in the etching of silicon in a chorine plasma for semiconductor device processing. In a typical cmos device a ~0.5 μm layer of polysilicon (which will ultimately form the gate electrode) is deposited on top of a much thinner layer of SiO_2 (the gate oxide). The gate is then formed by etching. An attractive etch process must simultaneously maximize the removal rate of silicon while minimizing both the etching of and damage to the underlying oxide. In addition the resist removal rate must be low enough to maintain the feature definition needed for submicron scale devices. For economic reasons, Si etch rates of 0.3–0.6 μm per minute are needed. At the same time rates ~100 times lower for oxide and ~5 times lower for resist are desired. The best ion energy range for high Si/SiO_2 selectivity is probably in the range of 20–40 eV.[29] Oxide selectivies of 280 have been observed in an optimized ECR reactor.[19] The low ion energies well also help avoid lattice damage to the gate oxide.

Directional etching is needed for producing the needed device geometries when the characteristic feature size is the same as the layer thickness. Otherwise the features defined by the mask are distorted. The low pressures of ECR source operation help achieve directional etching by minimizing scattering of gas species to feature side walls and by allowing ion energy control. Chlorine based processes are good candidates for directional etching because at room temperature and low pressure chlorine free radicals do not spontaneously etch silicon[32] and the intrinsically anisotropic character of an ion dominated etch process can be utilized.

For equipment design, feed material throughput is an important consideration at low pressures. As both the wafer diameter and desired etch rate increase, the pumping speed may become a limiting factor. For example, an etch rate of 5000 A/min over an 8" diam Si wafer would, at 1 mTorr, require a pumping speed of ~400 l/sec for the etched Si material alone. Additional pumping would be required for unused process gas.

B. Example: Etch selectivity of Si/SiO_2

Etch selectivities have been measured in a Cl_2 based Si etch system. The system is a combination of an Astex mirror field source[28] and auxiliary magnets to improve radial uniformity. These magnets are unlikely to affect the qualitive trends discussed below. For these experiments the upper and lower source magnets were positioned -0.015 m above and 0.29 m below the vacuum surface of the microwave window with currents of 200 A and 170 A respectively. These positions and currents were used for the calculations shown in Fig. 1. The chlorine flow rate was 20 sccm at a pressure of 0.37 mTorr before striking a plasma. The pressure was chosen to allow illustration of the importance of ion energy control for semiconductor etch applications using in situ reflectometry as the sole film thickness measurement technique. The selectivities of Si/SiO_2 obtained (up to ~10) are inadequate for many manufacturing processes, but higher selectivities are obtainable by using different operating conditions[17] as well as different source configrations.[19] The pressure with a plasma was approximately 0.2 mTorr when silicon was being etched and 0.24 mTorr when oxide was under process. All pressures were measured in the process chamber downstream of the mirror source and behind the auxiliary magnets.

The key feature of the source is the ability to control the ion energy down to a few tens of eV and access the window of ion energy which yields improved selectivity of Si/SiO_2. The lowest possible energy is determined by plasma space potentials. Source Langmuir probe characteristics have been taken and analyzed using the same approach as described in ref 28. Under conditions similar to those etch experiment described above, the difference between the space and floating potentials is typically 20–25 volts. Plasma densities measured ~2 cm above the wafer were $\sim 2 \times 10^{11}$ cm^{-3}, and electron temperatures were ~2.5–3 eV. Additional ion energy was provided by applying 13.56 MHz rf power to the floating wafer holder. The average dc voltage produced, V_{dc}, was measured at the holder. The exact relationship between V_{dc} and the incremental energy the bias gives to ions is not well understood because the wafer itself is insulated from the chuck and the rf power is capcitively coupled to the wafer front surface. Thus, only qualitative trends for ion energies may be inferred from measurements of plasma potentials and V_{dc}.

Silicon etch rates were measured by taking the time between minima in the reflected light of a normal incidence 785 nm solid state laser. Figure 3 shows a typical reflected light signal. Plasma light contributes to this signal as can be seen by the increases in reflected light when the plasma is on. During periods a and e, the laser is on but the discharge is off. The minima seen in time interval b occurs during polysilicon etching when the the phase shift in reflected light from the top and bottom surface of the polysilicon is π (one half wavelength path difference). Two consecutive minima in Fig. 3 corresponds to a thickness of 97.5 nm assuming an index of refraction of 2. After the roughly 400 nm of silicon clears, a slower and less distinct variation in reflected light is seen in time interval c. The variation consists of a slow rise, a maximum, and a fall that takes about one third the time of the rise. The constant level of reflected light in interval d indicates reflection from a single interface and signals the removal of the approximately 100 nm of oxide that is typical of the 6" test wafers used in this experiment. The time for the oxide to clear obtained by analyzing this signal typically has an estimated uncertainty of 2–3% because of the relatively gradual changes in slope. Oxide thicknesses of 100 nm were used to estimate rates based on measurements of similarly processed wafers.

Another indication of oxide etching was observed in the operating pressure, which increased about 20% when oxide was first exposed to the plasma and then fell back to the original value at about the time the oxide layer had cleared. The lower pressure present when Si is being etched may be due to the greater number of chlorene atoms tied up in the form of $Si\ Cl_4$ (as opposed to bein present as the Cl_2 feed gas). Since the interferometer only monitors the central portion of the wafer, monitoring the pressure was useful for checking global etch response. Etch rates determined using a the pressure measurement agreed to those obtained from the interferometer to within 5%.

Polysilicon and SiO_2 etch rates were measured for applied biases V_{dc} in the range 10–80 V. Measurements were attempted with no applied bias but the silicon etch rates were observed to decrease as a function of time. This is likely due to the competition between etching and the deposition of polymer films formed from etched photoresist remnants (which has been seen in SEM examination of wafers from similar experiments).

As shown in Fig. 4, both the silicon and oxide etch rates decrease with decreases in V_{dc} (and thus ion energies). The selectivity of Si with respect to SiO_2 is shown in Fig. 5

and increases sharply at low V_{dc}. As previously mentioned, the selectivity of about 10 at the lowest energy in this configuration is less than desired for submicron feature etching and or configurations. It should be noted that hydrocarbons from the resist material, which are observed to decrease apparent Si etch rates, may also enhance the etch rate of SiO_2 due to chemical interactions.[17]

IV. Summary

ECR plasma sources are being used for an increasing variety of materials processing applications. They are well suited for those applications which require control over ion energies while still maintaining high current densities (10s of mA/cm^2) at ion energies less than 100 eV. Selectivity measurements using an ECR source show the importance of ion energy control for Si etching using Cl-based chemistries.

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Figure Captions

Figure 1. Magnetic field lines and surfaces of constant magnetic field modulus for an ASTeX ECR plasma source with the upper coil current at 200 A and the lower coil current at 170 A. The coil seperation is 0.305 m. The magnetic field labels are in Tesla.

Figure 2. Outline drawing for a simple ECR source coupled to a permanent magnet multipole "bucket".

Figure 3. Reflected light from the central region of a 6" silicon wafer. The bias voltage for this run was 70 V. The various regions are : (a) and (e) laser on with plasma off; (b) polysilicon etching; (c) SiO_2 etching; (d) underlying Si substrate etching (polysilicon and SiO_2 have been cleared).

Figure 4. Polysilicon and SiO_2 etch rates as a function of applied bias.

Figure 5. Selectivity (polysilicon etch rate divided by SiO_2 etch rate) as a function of applied bias.

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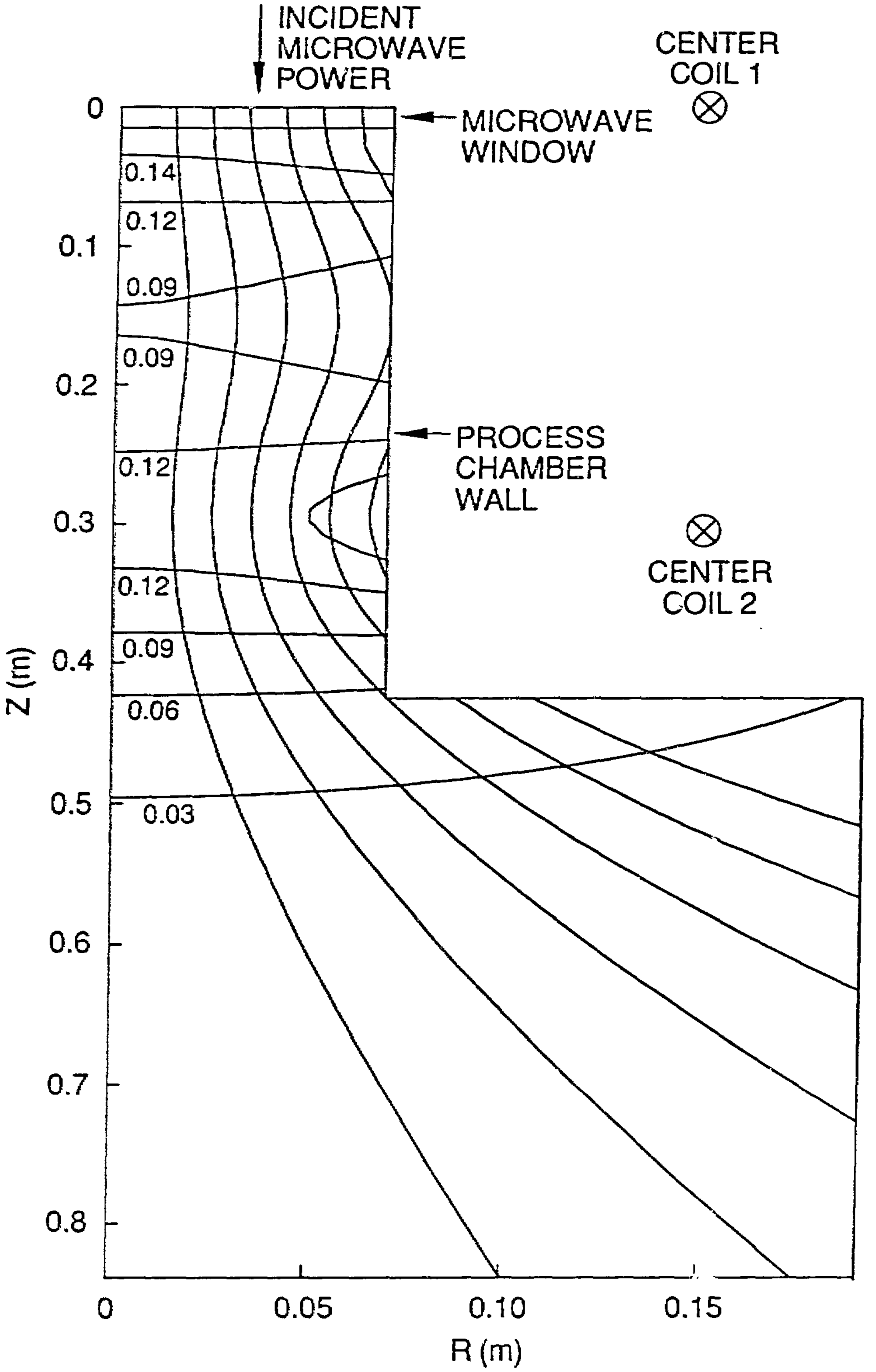

Fig 1

ECR PLASMATRON

ECR PLASMATRON

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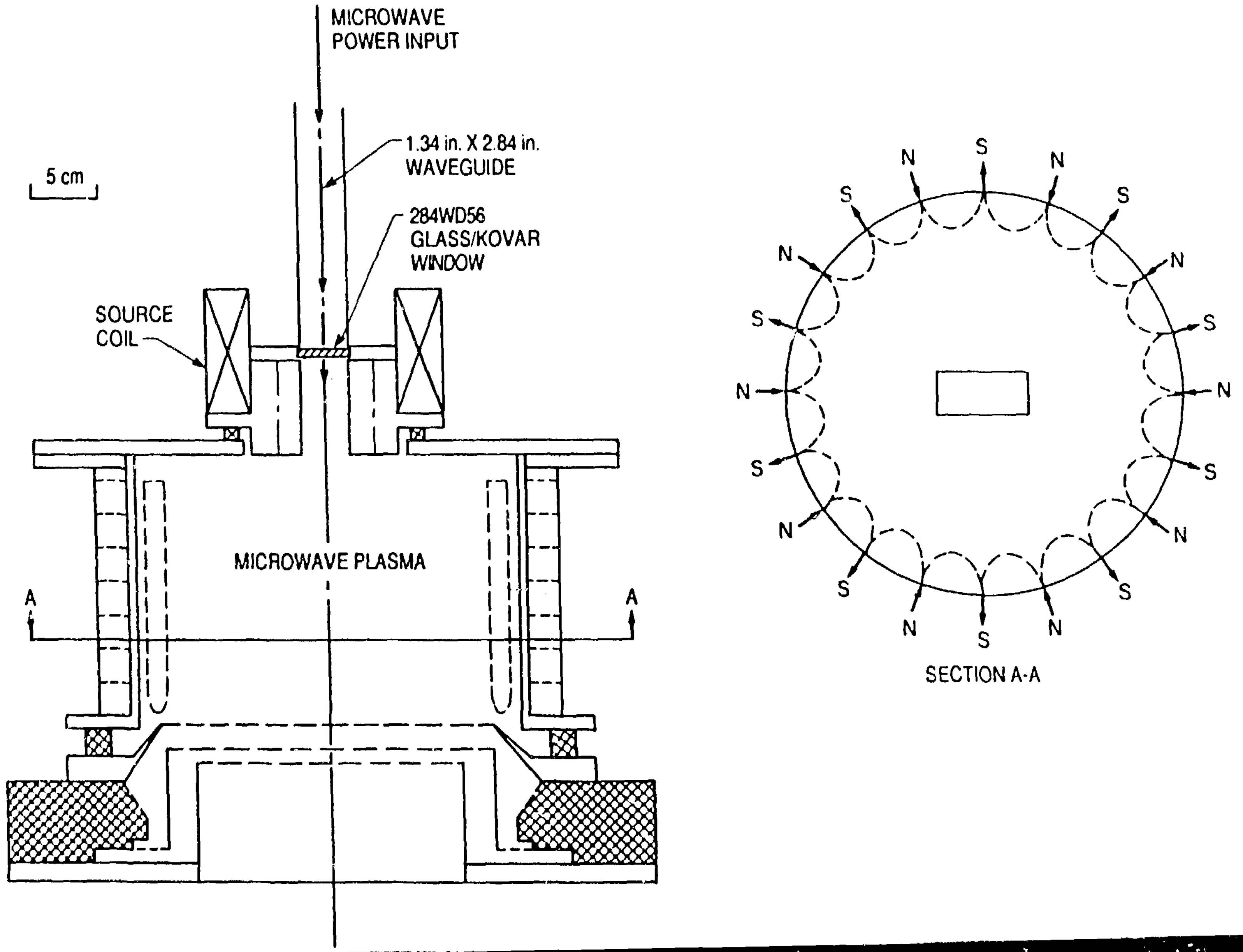

Fig 2

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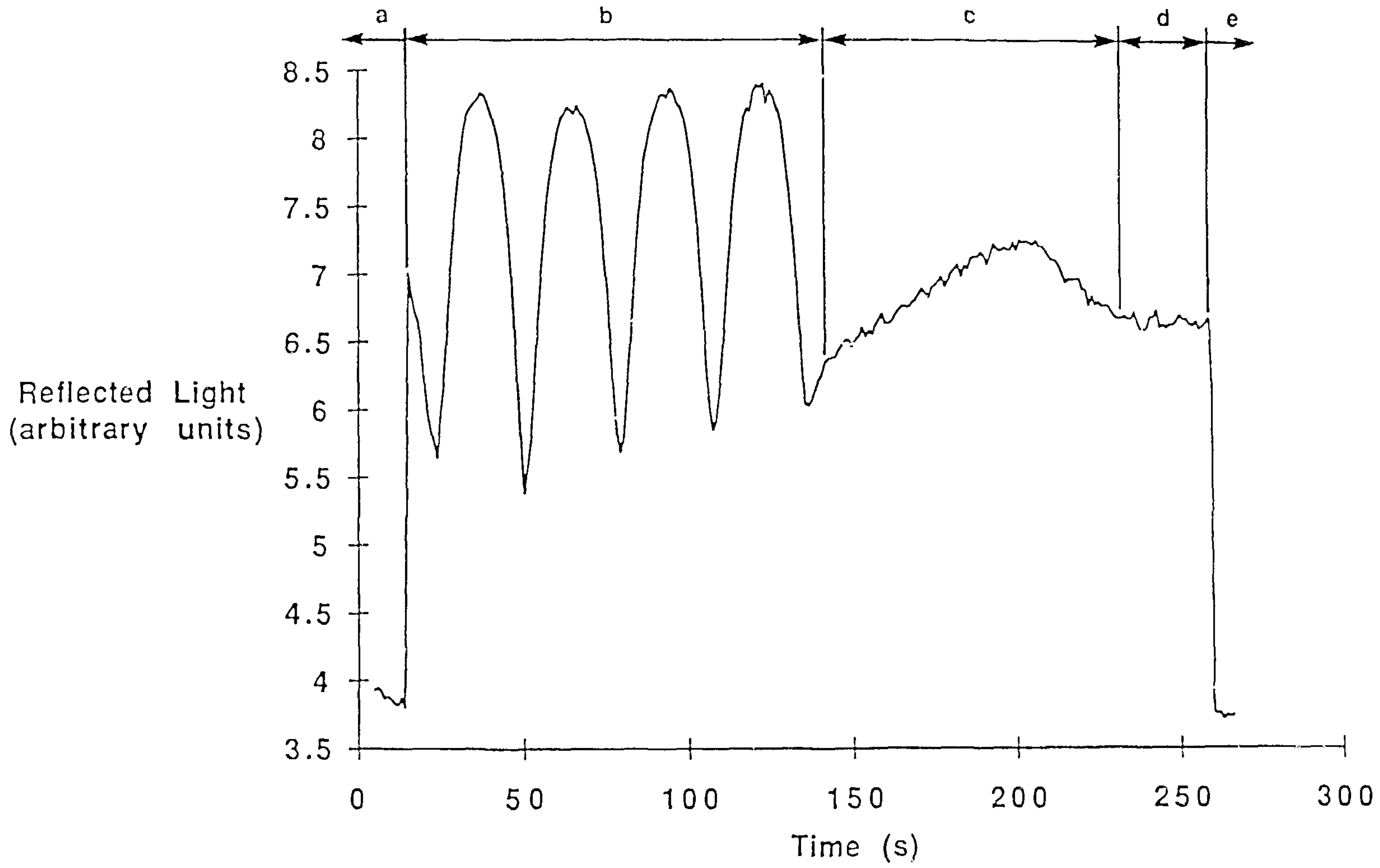

Fig 3

Fig 3

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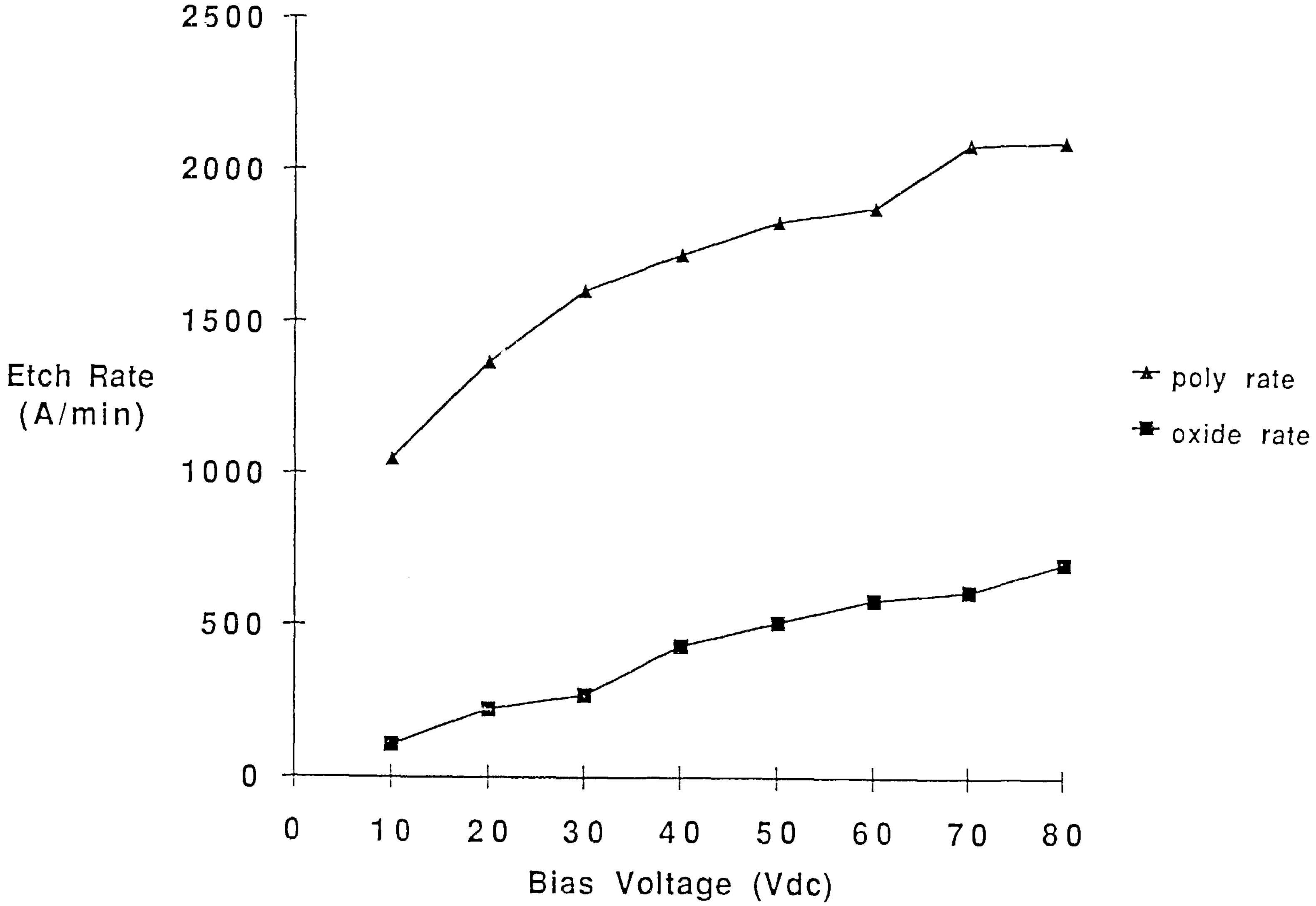

Fig 4

Fig 4

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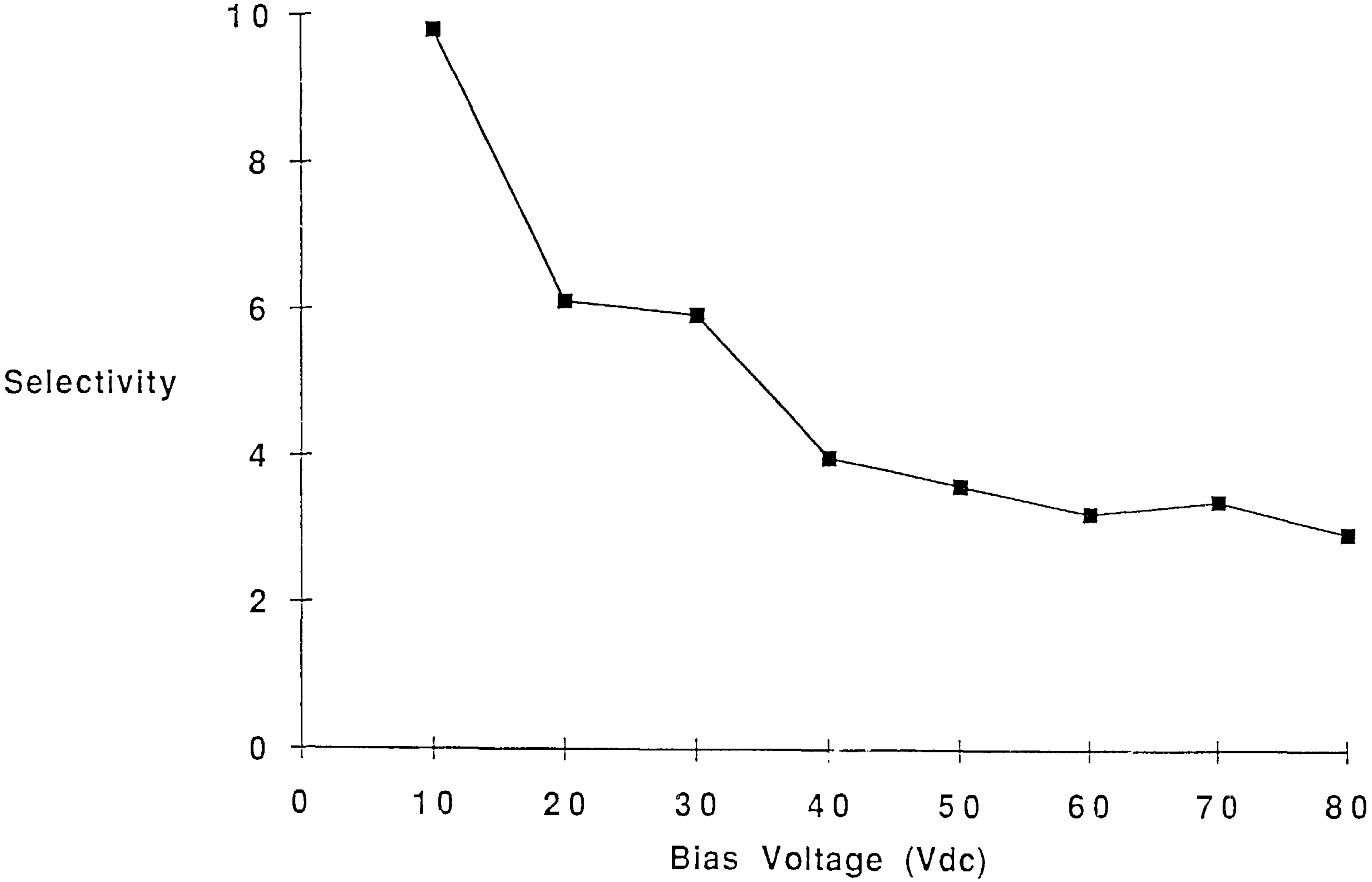

Fig 5