Review of inductively coupled plasmas for plasma processing

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Abstract. The need for large-area, high-density plasma sources for plasma-aided manufacturing of integrated circuits has created a renewed interest in inductively coupled plasmas (ICPs). In this paper several ICP reactor geometries are briefly reviewed. Typically, inductive coupling of RF power (0.5–28 MHz) can produce ion densities in excess of 10^{12} cm^{-3} even at sub-millitorr pressures. Existing electromagnetic field models of ICPs are examined and found to be in reasonable agreement with experimental results. Sputter deposition, anodic silicon oxidation and polymer etching using ICPs are also described. It is concluded that ICPs are promising candidates for meeting the future requirements of plasma processing, although considerable process development, plasma characterization and modelling are still needed.

1. Introduction

For over 100 years inductively coupled plasmas (ICPs) have been generated and studied. Recently the trend toward high-rate, single-wafer processing in integrated circuit (IC) fabrication has motivated the development of low-pressure (<1 Torr) ICPs for plasma-aided materials processing applications. The requirements for modern processing plasmas include high densities of ions, electrons and radicals, excellent uniformity over diameters of at least 20 cm, low and controllable ion energies and negligible contamination from reactor sputtering or particulate generation. A review of inductively coupled plasmas reveals that most of these requirements can already be met using a readily available RF (13.56 MHz) heating frequency and relatively simple source designs.

It is naturally desirable to understand the physics of the ICP as an aid to controlling the plasma process. Since low-pressure ICP implementations for IC processing plasmas are relatively new, these sources have not been investigated as extensively as other high-density plasmas such as electron cyclotron resonance (ECR) plasmas [1] and helicon wave plasmas [2, 3]. For an overview of high-density plasma sources the reader is referred to [4]. This paper contains a brief review of the current understanding of the properties of ICPs with an emphasis on low-pressure, plasma-processing applications.

2. Review of inductively coupled plasma technology

As the name implies, the inductively coupled plasma uses an inductive circuit element adjacent to (or immersed inside) a discharge region in order to couple energy from an RF power source to an ionized gas. The inductive circuit element is typically a helical or spiral-like conductor. An additional electrical reactance is used to tune the inductor such that an electrical resonance at the RF driving frequency is obtained. Properly implemented, the resonant circuit causes large RF currents to flow in the inductive element. The RF magnetic flux generated by these currents then penetrates into the adjacent discharge region. Using Faraday's law, $\nabla \times \boldsymbol{E} = -\partial \boldsymbol{B}/\partial t$, one can see that the time-varying RF magnetic flux density ($\boldsymbol{B}$) induces a solenoidal RF electric field ($\boldsymbol{E}$). It is this 'inductive' electric field which then accelerates free electrons in the discharge and sustains the plasma.

Since the inductive coupling element is driven in an electrical resonance condition, one can expect high potentials to exist on the structure. Such RF potentials will lead to capacitive coupling to the discharge as one would observe in RF planar parallel-plate plasma reactors. Capacitively coupled plasmas are characterized by high voltages and observable sheaths. Ions are accelerated across the sheaths to the walls at high energy and can cause sputtering and heating of the walls. It is not uncommon to observe weak, capacitively coupled *E-discharges* in inductively coupled plasma sources at low absorbed powers [5–7]. As RF power is increased, a sudden increase in luminosity and density is observed at pressures above ~30 mTorr [6], signaling the onset of inductive coupling or the *H-discharge*. The mode of coupling (capacitive or inductive, E or H) has frequently been a matter of debate since the original inductive plasmas [7]. Some implementations of ICP reactors attempt to minimize the degree of capacitive coupling (and its negative side-effects) by placing split Faraday shields between the inductive coupler and the discharge wall. Since high potentials exist on the inductive couplers, it is arguable that any ICP is *entirely* inductively coupled and, for the purpose of this review, high-density plasma sources which may be only partly inductively coupled will be considered as ICPs.

In what follows an attempt has been made to classify the various forms of inductively coupled plasma sources. Conspicuously absent from the listing below is the helicon wave source [2, 3] which is sometimes referred to as a resonant inductive plasma etcher [8, 9] (RIPE). In this source, however, the plasma is magnetized longitudinally by solenoidal electromagnets, and coupling is achieved by an RF transverse electromagnetic helicon wave. The divisions among non-magnetized ICPs reviewed here are made primarily along geometrical features and are:

(i) helical inductive couplers—cylindrical plasmas;
(ii) helical resonators—cylindrical plasmas;
(iii) spiral inductive couplers—planar plasmas;
(iv) immersed inductive couplers;
(v) transformer-coupled plasmas.

2.1. Helical inductive couplers

Historically, Hittorf is credited by Eckert [10] with producing the first plasma by induction using a coil surrounding a tube in 1884. These early inductive plasmas were often referred to as 'ring' discharges since the limited skin depth of the exciting field in the discharge caused the periphery to glow more brightly. More recently, high-pressure (~1 atm) induction plasmas or 'induction arcs' have been extensively studied and used. Eckert [11] gives a comprehensive review of high-pressure ICPs. Applications include spectral chemical analysis, plasma-assisted chemical synthesis, crystal growth and thermalization of gases to produce thrust from a plasma jet. At high pressures, however, the plasma is dominated by volume recombination rather than diffusion which results in a non-uniform, small-volume plasma. In addition, high-pressure arcs are characterized by high neutral gas temperatures (1000–10 000 K). These properties make the induction arc unsuitable for processing damage-sensitive, large-area wafers and dictate low-pressure operation.

The geometry of the helical-class ICP is shown in figure 1(*a*). The induced electric field within the plasma is azimuthal, forming closed loops about the axis, and the RF magnetic field is directed along the central axis of the discharge [5, 10, 12]. Several models [5, 11–13] have been published which describe the induction fields while taking into account such factors as finite conductivity and radial variation of plasma density. In general, the induction field is maximum at the plasma tube circumference and decreases monotonically toward the centre. The result at higher pressures can be a ring-shaped discharge as viewed along the axis. At low pressures, however, diffusion processes increase the plasma density near the centre, where the induction field is low, thus providing a more radially uniform discharge.

It is possible in the helical-class ICP for the high RF potential which forms end-to-end across the inductive coupler to produce an axial electric field through the discharge. The axial field will produce a weak capacitive discharge, particularly during low-power operation [5, 6]. A cylindrical conducting shield (Faraday shield) placed around the discharge chamber will short-out the axial electric field. Longitudinal slots must be cut from the shielding, however, so that the shield does not function as a *short-circuited secondary transformer* winding with the inductive coupler acting as the primary, thus inhibiting induction fields from the discharge region. When operated in the inductive mode, argon ion densities [6] in excess of 10^{12} cm^{-3} have been reported at 64 mTorr.

The barrel etcher [14] is a traditional plasma processing tool which is very similar in appearance to figure 1(*a*). Plasma ion density in barrel reactors is typically only of the order of 10^{10} cm^{-3} or less, suggesting that the coupling mechanism is capacitive. In addition, wafers are loaded into the centre of the cylindrical discharge vessel for processing where they would significantly disrupt the inductive fields. For this reason, plasma processing in helical inductive plasmas and helical resonators (discussed below) frequently occurs in a remote, downstream chamber which is separate from the plasma generation region.

2.2. Helical resonator

The helical resonator plasma source [15–18] also consists of a cylindrical discharge tube within a helical coil. The coil, however, is designed with an electrical length of $(\lambda/4+n\lambda/2)$ or $(\lambda/2+n\lambda/2)$, where $n=0, 1, 2, \ldots$ and λ is the wavelength of the excitation frequency. The former design is a quarter-wave resonator and the latter is a half-wave resonator. As shown in figure 1(*b*) the coil is within a conducting enclosure which provides a parasitic capacitance from the coil to ground. In addition, a trimming capacitor is usually connected between the coil and ground to adjust the capacitance to ground such that the structure resonates. Typically one end of the coil is grounded and, in the quarter-wave resonator, the other end is floating. In the half-wave design, both ends of the coil are grounded. RF power is applied at a centre tap of the coil. The presence of the discharge chamber and plasma within the helical resonator will perturb the resonant frequency of the reactor. A treatment of this perturbation is given in [19].

Although there is currently some debate as to whether the helical resonator is truly an inductively coupled plasma, high-density plasmas can be generated using a split Faraday shield (described above) between the coil and the plasma. This shield will short-out capacitive fields and allow primarily inductive excitation of the discharge. In addition, ion densities of 10^{10}–10^{12} cm^{-3} have been reported in commercially available helical resonators [18] thus exceeding densities produced by capacitively coupled plasmas (typically ~10^{10} cm^{-3}).

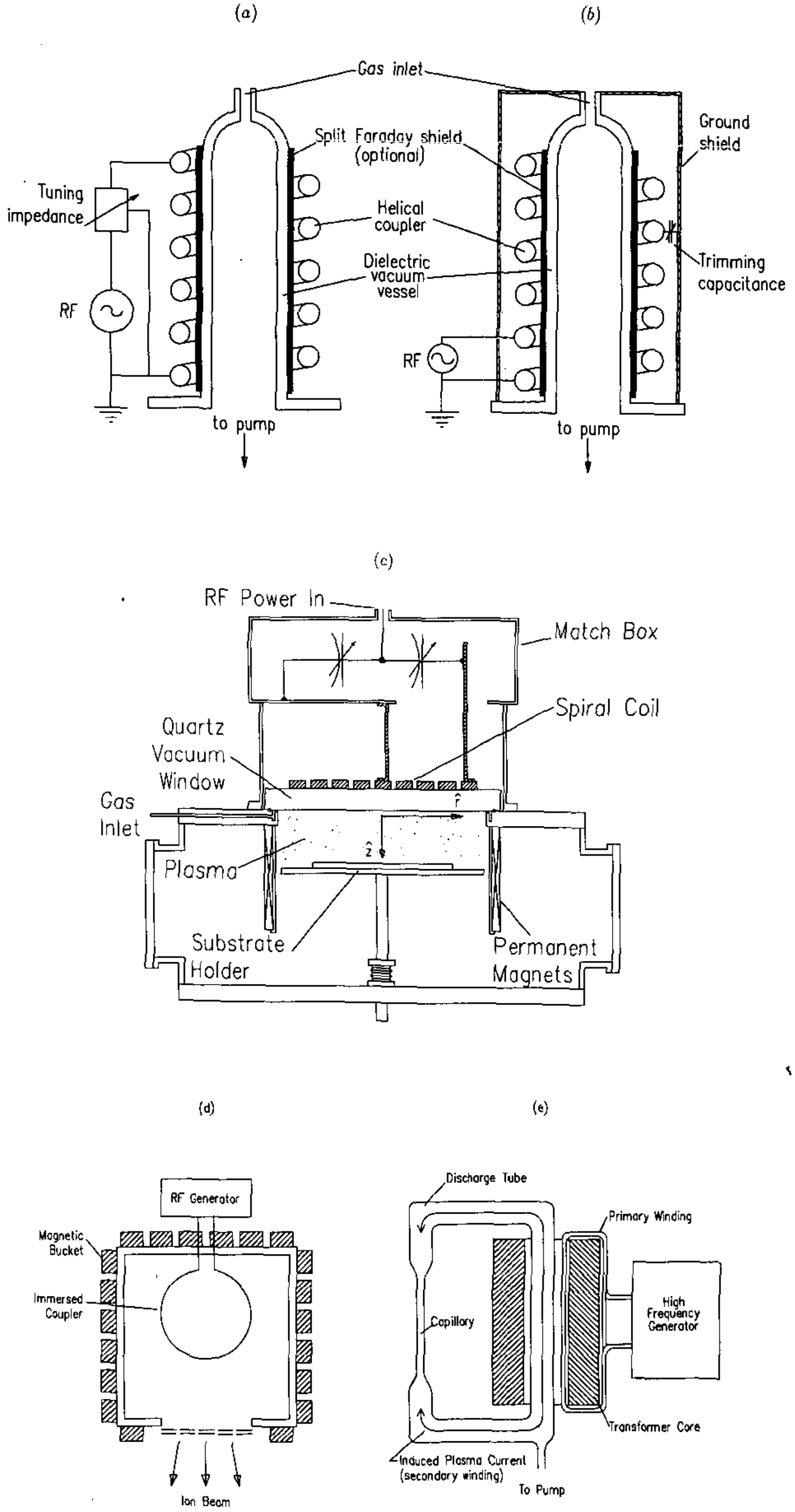

Figure 1. Cross-sectional schematic diagrams of various inductively coupled plasma reactors: (*a*) helical coupler, (*b*) helical resonator, (*c*) spiral coupler, (*d*) immersed coupler and (*e*) transformer-coupled plasmas. See text for details and references.

2.3. Spiral inductive couplers

In processing applications where it is desirable to generate uniform plasmas over large, planar areas or in ion sources where one wishes uniform ion generation over planar extraction grids, spiral-like inductive couplers which lie in (or nearly in) a plane have been developed [20–23]. A typical planar design is shown in figure 1(*c*) where a spiral-like coil (shown in cross section) is separated from the low-pressure discharge chamber by a dielectric (typically quartz) vacuum window. A capacitance in series with the spiral inductor is tuned such that the driving circuit resonates at the RF frequency. These reactors sometimes use permanent-magnet multipolar buckets in the discharge chamber to confine the plasma, improve uniformity and increase the discharge density. The effects of capacitive coupling between the coil and the plasma are reduced by using a thick-cross-section dielectric window.

The geometry of the spiral ICP holds particular advantages in processing of planar surfaces such as wafers. Since the skin depth of a 13.56 MHz RF induction field is approximately 1–2 cm in plasmas with electron densities of the order of $10^{11}\,\mathrm{cm}^{-3}$, the substrate may be placed in close proximity to the inductive coil. Typically, the coil is separated from the plasma by a 1–3 cm quartz window and the substrate is positioned 5–10 cm below the window (2.5–10 skin depths). The induction electric field decays exponentially within the plasma such that the field strength is attenuated by a factor of at least 12 (i.e. exp 2.5) at the substrate. By processing in close proximity to the region of plasma generation, plasma losses such as electron–ion and neutral–neutral recombination are reduced as compared to remote, downstream processing. This results in improved ion generation efficiencies as measured *at the substrate*. For the source in figure 1(*c*), argon-ion generation efficiency measured at the substrate varies from 150–300 eV/ion for argon densities of $(1–4)\times10^{11}\,\mathrm{cm}^{-3}$ at 5 mTorr and 100–1000 W RF power. Although it can be argued that RF power is inexpensive relative to the other costs of IC fabrication, reduced power absorption may provide other benefits. In downstream source configurations, for example, the plasma in the generation region may typically be an order of magnitude more dense than at the substrate [24]. Such an excessively dense plasma in the source region may increase sputter contamination, UV damage and neutral gas heating at the substrate. Although the principle is not proved, it is at least intuitively appealing to produce a plasma of exactly the proper density, and no more, at the point of use. Examples of the performance and modelling of planar, spiral ICPs which approach this ideal are given later in the paper.

2.4. Immersed inductive couplers

In the ICPs discussed so far, the inductive coupling element has been physically outside the discharge region. In the immersed-coil class, the inductor is positioned within the plasma vessel (figure 1(*d*)). This design has a distinct advantage in metal sputtering [25] applications. Metal deposition on the dielectric plasma-vessel walls of non-immersed ICPs eventually suppresses plasma generation by acting as a single-turn, short-circuited secondary winding which is closely coupled to the inductive driver. Although Yamashita [25] reports no measurable impurities in the metal films deposited by immersed ICP sputter deposition, contamination sputtered from an immersed inductive element is a concern in other processing applications such as etching and deposition. Immersed coils have successfully been used in ion beam sources [26–28] where a loop antenna is located within a magnetic bucket vacuum vessel (see figure 1(*d*)). To prevent sputter erosion of the antenna, glass cloth is fused to the metal inductor. Helium-ion densities of 2×10^{11}–$5\times10^{12}\,\mathrm{cm}^{-3}$ at 0.5–5 mTorr have been reported in pulsed RF (3-100 kW, 1 MHz) immersed ICP ion sources [26].

2.5. Transformer-coupled plasmas

ICPs have also been used in laser design [29–31] where a ferrite core transformer couples low- or high-frequency (2.5 kHz–1 MHz) energy to a ring-shaped plasma chamber (see figure 1(*e*)). Here the reader may observe that the plasma functions as a single-turn secondary winding around the closed path of the vacuum vessel. The induction electric field resides along the axis of the tube, rather than in the azimuthal loops of the helical and spiral ICPs. Reference [30] describes an ICP with a similar closed-loop plasma tube, but a single-turn, air-core primary winding is used. This implementation has been operated from 3.5–28 MHz. The plasma in these configurations is most intense in the narrow *capillary* region which is typically 1–3 mm in diameter. For laser operation an optical cavity is positioned to include the capillary volume. While the narrow cylindrical geometry described here is not appropriate for large planar areas encountered in semiconductor fabrication, it may prove useful for continuous-strand processing systems and other applications.

3. Modelling of ICPs

The simplest model of the ICP is a discrete circuit element model known as the transformer model [5] shown in figure 2. In this model the inductive coupling structure is described as an N-turn primary transformer winding with self-inductance, L_p. The high-density plasma is modelled as a single-turn secondary winding and a series-connected plasma impedance, Z_{plasma}. The coupling coefficient, K, between the primary and secondary windings may approach unity for helical, immersed and transformer-coupled reactors. For spiral-like inductive couplers, K may be somewhat less than one [20]. This reduction in coupling coefficient is due to the leakage magnetic flux from the primary which does not intersect the secondary defined by the plasma. The transformer

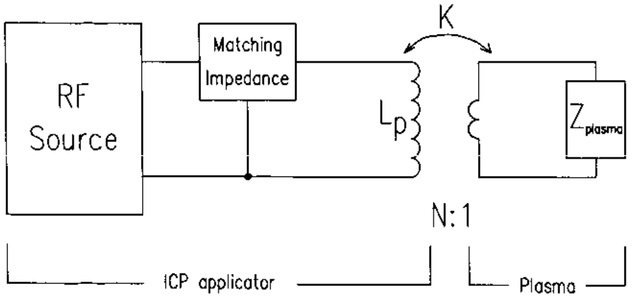

Figure 2. Schematic diagram of the transformer model of inductively coupled plasmas [5].

model is sufficient for relating external circuit parameters such as coil current and voltage to the 'plasma impedance', but does not directly describe the fields within the plasma or any plasma physics.

More sophisticated electromagnetic models have been developed to describe the induction fields within the discharge. Thomson [13], in one of the earliest theoretical treatments of the ICP, produced analytical expressions for the field required to sustain a plasma by induction. In his work, Thomson concludes that 'it does not require a very intense magnetic field to produce he discharge'. In the same work, Thomson also identified the tendency of currents induced near the periphery of the discharge to shield the central regions from induction currents. Recent measurements [32] in spiral-like ICPs (see figure 1(*c*)) are shown in figure 3. Notice that the 13.56 MHz magnetic flux density is quite low at only a few gauss. The corresponding induced electric field is of the order of only 4–8 V cm^{-1}. Figure 3 also demonstrates the shielding of the inductive fields by plasma currents. Induction electric fields which are parallel to a planar plasma surface are expected to decay spatially with an exponential dependence and a decay constant given by $\delta \simeq c/\omega_{pe}$, where c is the speed of light in a vacuum and ω_{pe} is the electron plasma frequency [33]. The full curves in figure 3 are exponential least-squares fits to the experimental data which confirm the theoretical shielding depth (or *skin depth*) of the induction field.

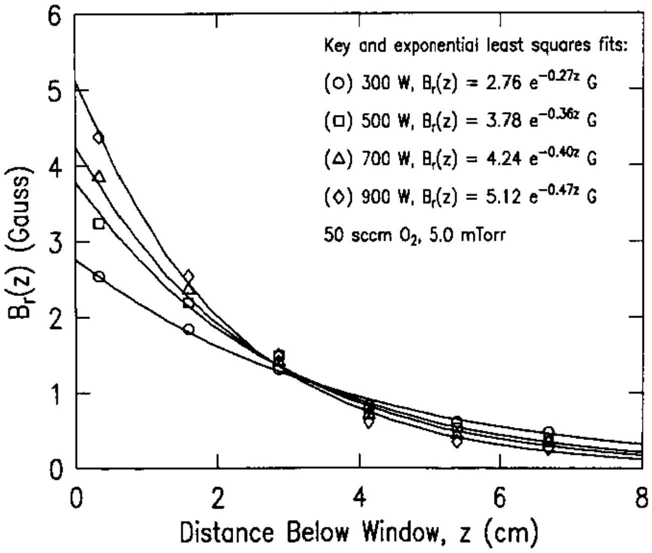

Figure 3. The radial component of the induction magnetic flux density decreases exponentially away from the spiral-shaped coupler.

The Thomson [13] model assumes uniform and real conductivity across the helical-type ICP discharge diameter. Eckert [10] refined this model by combining positive column diffusion theory with the electromagnetic model and the effects of finite collision frequency. Henriksen *et al* [12] offer a similar solution with the assumption of a parabolic radial electron density profile.

The preceding models of helical ICPs all make an *a priori* assumption that the magnetic field is axial and the electric field and current are entirely azimuthal. For the spiral-like, planar ICP (figure 1(*c*)) these simplifying assumptions are not easily justified. A schematic representation of the induction electric and magnetic fields for the spiral coil ICP is shown in figure 4. The reader may observe that the *B*-field is not directed entirely along the axis as in helical coil ICPs. The RF fields, however, can be numerically modelled by solving Maxwell's equations using finite element analysis (FEA). Solutions for the electric field are shown in figure 5 for such a planar ICP [32]. The electric field in a plane 2.5 cm below the vacuum window is shown by arrows where the relative size of the arrow is proportional to the strength of the field. The square-spiral coil is shown in outline to assist the reader. This model is a three-dimensional numerical solution to Maxwell's equations assuming a cold, collisionless and uniform plasma with a relative permittivity given by $\varepsilon_r = 1-(\omega_{pe}/\omega)^2$ where ω_{pe} is the electron plasma frequency and ω is the RF frequency. Direct measurement of the magnetic flux by a small loop antenna, movable within the plasma, has experimentally confirmed the accuracy of this model. It is interesting to note that the electric field is in fact dominantly azimuthal within the bulk of this high-electron-density plasma. One would expect that axial electric fields due to capacitive coupling from the coil to the plasma would quickly decay over the distance of several Debye lengths [33] (which is of the order of 100 μm). Nonetheless, such capacitive fields may play an important role in the plasma interactions at the window such as sputtering.

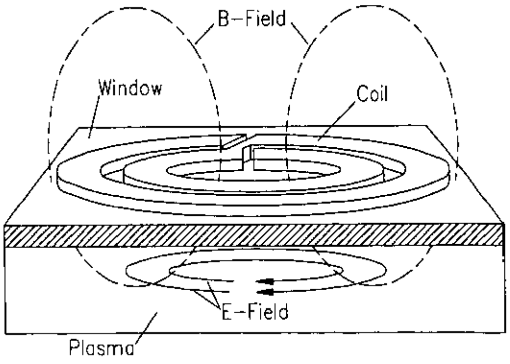

Figure 4. Schematic representation of the induction fields for a planar, spiral coupler above a dense plasma.

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