

A high-density Inductively-Coupled Remote Plasma System for the deposition of dielectrics and semiconductors

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Abstract— We recently built an Inductively-Coupled Remote Plasma-Enhanced Chemical Vapor Deposition (ICPECVD) system for deposition of dielectric and semi-conducting layers at low substrate temperatures (~150 °C). The deposition system was designed to operate either in a chemical-vapor-deposition (CVD) or atomic-layer-deposition (ALD) mode. This apparatus will be used to study how the physics and chemistry of the deposition process influence the electrical and physical properties of the deposited films.

Index Terms— CVD; PECVD; high-density plasma; ICPECVD; ICRPECVD; ALD; thin film

I. INTRODUCTION

THE fabrication of electronic devices at relatively low deposition temperatures (100-150 °C) becomes increasingly important. By doing so, one can fabricate devices on glass [1] or polymer substrates [2-4] or one can add extra active functionality onto the back-end processes of standard ICs (a “System-On-Chip” kind of fashion) [5]. In order to realize good devices one should deposit high-quality dielectrics and semiconductors (with respect to their electrical performance), which is a challenge at such low temperatures.

In a conventional low pressure chemical vapor deposition (LPCVD) system, the energy needed for heterogeneous chemical reactions on the substrate is provided by heating. Typically temperatures of 700 °C and higher are needed. One can also deliver the energy in a non-thermal way, e.g. by plasma. In plasma, high concentrations of neutral radicals and ions can be formed. Due to their high reactivity, such species can react on the substrate surface at lower temperatures. Typical substrate temperatures in such a plasma-enhanced chemical vapor deposition system (PECVD) are 400 °C and lower.

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However, the temperature reduction has its price in a deteriorated layer quality. Reactions are not completed (i.e. not all the reaction products can desorb from the film), and/or formed bonds can be broken again by high-energy ions and electrons impinging on the growing film. To enhance the quality of layers grown by PECVD and further reduce the deposition temperature, remote high-density plasma-enhanced CVD (remote HDPECVD) has also been investigated intensively. The term *high density* plasma typically encompasses all sources operating with a gas ionization degree of a few percent (i.e. with ion densities above 10^{11} cm⁻³). The term *remote* denotes a situation in which the depositions are performed with the substrate located outside (or downstream) of the plasma-generation zone. The immediate benefit is that the substrate is less subjected to bombardment with high-energy ions and electrons, whereas the fluxes of radicals are still sufficiently high to maintain reactions at the substrate. A second benefit is the possibility to inject precursors with low dissociation energy outside of the plasma-generation zone. Modern deposition systems meeting all these requirements employ the electron cyclotron resonance (ECR) and inductively coupled (IC) plasma sources. These systems can be operated typically below 300 °C.

To enhance film quality, one may also use atomic layer deposition (ALD). In this technique gaseous precursors are successively introduced to the substrate surface in a cycled regime. Between cycles, the volatile reaction products are flushed from the reactor by purging with an inert gas. Only one precursor is normally introduced during a cycle. An ideal ALD process has a self-limiting mechanism in which the growth surface becomes saturated with precursor or reactant molecules, so that film growth automatically stops (or ‘self limits’) at one monolayer. ALD relies on surface exchange reactions between chemisorbed precursor fragments and adsorbed reactant molecules. The surface-controlled growth in ALD ideally leads to high-quality films and highly uniform coverage of non-planar surfaces with high aspect ratios. Like in CVD, activation energy needed for surface reactions to

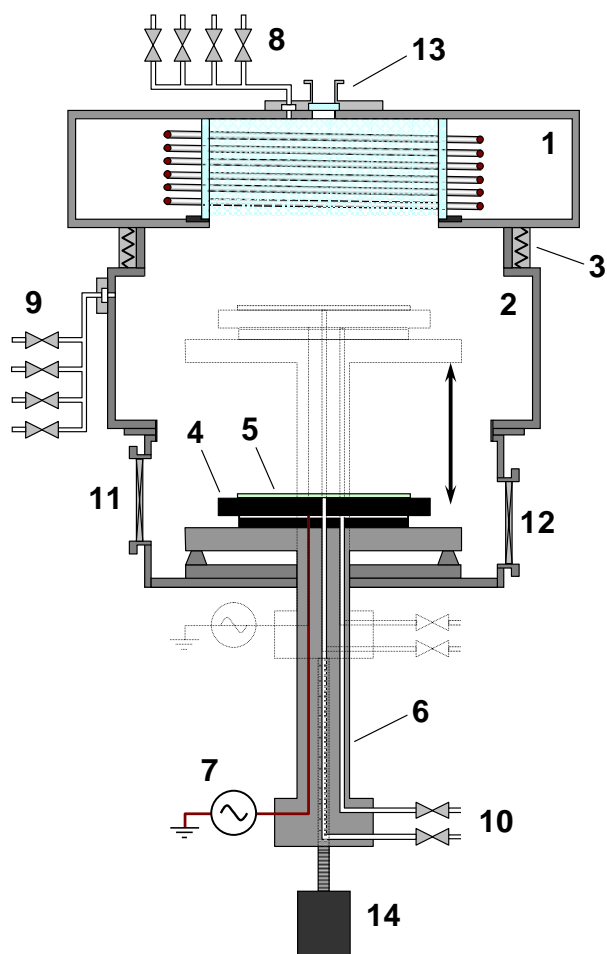


Fig. 1. A schematic drawing of the remote-plasma CVD system: (1) ICP source, (2) diffusion chamber, (3) electrostatic lens, (4) chuck and susceptor, (5) wafer, (6) motor-driven arm, (7) RF-source to bias chuck, (8) gas-inlet at plasma, (9) gas-inlet at diffusion chamber, (10) gas-inlet to control pressure between wafer and susceptor and between susceptor and chuck, (11) gate valve to load lock, (12) connection to pumping line, (13) viewing port, (14) linear motor; the gas distribution system, load lock and vacuum pumps are not drawn.

occur can be delivered by substrate heating or by the bombardment from a (high-density) plasma. For example, the thermal-ALD of aluminum oxide from trimethylaluminum requires a typical substrate-temperature of 300 °C, whereas a temperature of only 150 °C is needed when plasma-enhanced ALD is applied [6]. One could also expect a larger growth-per-cycle value for PE-ALD compared to thermal-ALD, since the plasma species may activate surface sites to suitable bonding sites quite effectively.

We recently built a remote ICP-activated deposition system for deposition of thin films in a CVD- and/or ALD-mode. Both are promising techniques to deposit layers with good electrical properties at low substrate temperatures. This paper describes our system and discusses some typical deposition conditions and mechanisms.

II. DESCRIPTION OF THE SYSTEM

Figure 1 schematically shows the experimental set-up. The

inductive-coupled plasma source (supplied by Adixen; 13.56 MHz, max. power of 2 kW) is placed on top of the diffusion chamber. The wafer is placed in the load lock on a molybdenum susceptor and, after a pump-down cycle, transferred into the deposition chamber by an automated arm and placed on the chuck. The chuck position is at the bottom of this chamber. The chuck can be heated to 400 °C, but the targeted deposition temperatures should not exceed 150 °C. The temperature is controlled by a PID (proportional-integral-derivative) controller via a thermo-couple inserted into the chuck. The wafer is mechanically clamped to the chuck and an argon backing pressure of 8-10 Torr between the susceptor and the chuck and between the wafer and the susceptor guarantees a fairly good heat transfer between the chuck and the wafer [7]. The chuck can be RF-biased and can be moved upwards into the diffusion chamber towards the plasma source. Furthermore, in Figure 1 two gas inlets can be distinguished: the first inlet is situated above the plasma and the second in the diffusion chamber. An extensive gas distribution system (not drawn in the figure) will supply the gases to the deposition system, eventually in a pulsed mode. The system is evacuated with an oil-free turbo molecular pump (Adixen ATH 1300 M, effective pumping speed 800 l/min) backed by a dry pump (Adixen ACP 40 G). The measured base pressure in the deposition chamber is $3 \cdot 10^{-7}$ mbar. A set of Pfeiffer capacitance gauges are used to measure process pressures accurately (Pfeiffer CMR 261 and CMR 263) and a combined cold wall and Pirani gauge measures from base pressure to atmospheric pressure (Pfeiffer PKR 261). Via the load lock, our system is coupled to two thermal ALD-systems (intended for ALD of metal barriers and dielectrics) and to an XPS and AFM/STM measurement tool. These measurement tools allow us to study film properties without a vacuum break and, therefore, without a deterioration of the film quality due to the contact with air.

III. A TYPICAL DEPOSITION SCHEME: DEPOSITION OF SILICON NITRIDE IN THE ICRPECVD-MODE

In this paragraph an example of a typical deposition scheme is sketched. A wafer is introduced in the system and heated up to 150 °C. To deposit silicon nitride (Si_3N_4), we introduce a mixture of argon (~100-500 sccm Ar) and nitrogen (~10-50 sccm N_2) in the plasma whereas silane (~1-5 sccm SiH_4) is introduced downstream in the diffusion chamber. The deposition process can now be characterized by the following steps: (a) excitation and dissociation of N_2 to form nitrogen radicals, (b) diffusion of the radicals and excited species out of the plasma-generation region, (c) mixing and gas-phase interactions of those species with silane in the diffusion chamber (i.e., energy transfer from the species to silane molecules due to inelastic collisions) which produces silane radicals due to dissociation of silane, and (d) surface reactions at the substrate. At pressures in the mTorr-

range, the only occurring gas-phase reactions with silane are abstraction reactions (to form SiH₃, SiH₂, SiH and Si radicals) [8]. Gas-phase formation of particles containing Si-N or Si-Si bonds would have been more likely if we had introduced silane in the plasma region since silane dissociates more easily than argon or nitrous oxide. However, since typical pressures in our system are low (few mTorr) diffusion of silane in the plasma-generation region will occur anyhow and can only be suppressed to a small extent by a high flow-ratio of Ar/SiH₄. Silane and silane precursors adsorb on the substrate and are subjected to a flux of radicals, ions and electrons where they cause surface reactions to form Si₃N₄. Energy of the impinging ions and electrons can be controlled by manipulating the distance between the wafer and the plasma-generation zone and by applying an RF-bias to the chuck. By adjusting the bombardment energy with the energy determining the rate-determining step (H₂ desorption) we hope to grow high-quality silicon nitride films.

IV. A TYPICAL DEPOSITION SCHEME: DEPOSITION OF ALUMINIUM OXIDE IN THE ALD-MODE

A typical aluminum oxide (Al₂O₃) deposition in the plasma-enhanced ALD-mode could be as follows. A wafer is introduced into the chamber and heated to 150 °C. Sequential repetition of trimethylaluminum pulses (TMA) through the inlet in the deposition chamber and pulses of nitrous oxide (N₂O) through the gas-inlet at the plasma side will form the film in a layer-by-layer fashion, since the chemisorbed monolayer of TMA will be oxidized by oxygen radicals and ions. Pulse lengths of typical ALD-processes are in the range of 0.5-2 seconds. We will have to increase pulse lengths beyond those typical ranges since our deposition chamber is much larger. This will decrease our deposition rate but will not influence deposition chemistry.

V. PLANS FOR THE FUTURE

We plan to study how the physics and chemistry of the deposition process influence the electrical and physical properties of the films. To do so, we need to characterize the plasma by identifying and measuring plasma species and by relating plasma characteristics to the film properties.

The plasma will be studied by using a Langmuir probe. Ion and electron densities, electron temperature and electron energy distribution functions will be measured. These measurements will be performed in the diffusion chamber as a function of the distance from the plasma, as well as in the vicinity of the substrate to measure the influence of the RF-bias applied to the chuck.

Plasma species will be measured by an *in-situ* measurement method. We have not decided yet on the technique to be applied. We could apply absorption methods like infra-red (IR) absorption spectroscopy, but measuring absorption

spectra at such low pressures would require IR path lengths of several hundreds of meters. Furthermore, only molecules changing their dipole moments during their vibrations can be measured with IR technique. Optical emission spectroscopy in visible/UV range and fluorescence spectroscopy have the disadvantage that not all plasma species (e.g. SiH₃ and SiH₂) can emit light due to the selection rules and that absolute concentrations are hard to obtain. Energy-dispersive mass-spectrometry on the other hand, may be used to measure very low concentrations of ions and neutrals and their energies. Measurements can be distorted however by the short lifetimes of some radicals and collisions within the spectrometer.

Films will be characterized electrically and physically by a selection of methods e.g., C-V, I-V, Q_{bd} measurements and IR, XPS, (cross-sectional) TEM measurements.

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