Plasma Science and Technology
Room 201 ABCD W - Session PS2-TuA

Sustainability and Plasmas

Moderators: Phillipe Bezard, IMEC Belgium, **Sara Paolillo**, IMEC Belgium

4:15pm **PS2-TuA-9 Transient Assisted Processing (Tap): A Novel Scalable Plasma Processing Approach for Precision Etching and Sustainability in Semiconductor Manufacturing**, ***Atefeh Fathzadeh***, KU Leuven and Imec, Belgium; *Philippe Bezard,* IMEC, Belgium; *Stefan De Gendt,* KU Leuven and Imec, Belgium

New device architectures and computing paradigms require patterning a wide variety of materials with sub-nanometric precision and pattern fidelity, introducing new challenges. For instance, remaining Ga residues after patterning $InGaZnO_4$ channels cause higher gate leakage in 2T0C DRAM cells[1] or profile imperfections of NbTiN lead to higher power consumption and variations in critical current in Superconducting Quantum Computing (SQC)[2]. Among existing methods, Atomic Layer Etching (ALE) offers excellent precision; however, its high gas consumption and low throughput limit its practicality to ultra-thin layer (≤10 nm) applications. These challenges, coupled with environmental concerns of dry etching, have driven interest in developing more sustainable etching approaches.

Transient-Assisted Processing (TAP) provides a breakthrough solution[3]. TAP is a cyclic process based on reactant transients caused by interrupted gas injection after a short, sustained flow. The dosage, gas injection, and plasma ignition timings ensure an optimal ion-to-neutral ratio and control species formation (Fig1), enhancing process control, pattern fidelity and preserving surface composition. By exploiting the outgassing phenomenon, TAP significantly reduces gas consumption, including environmentally harmful gases, compared to ALE and Reactive Ion Etching (RIE). TAP has also proven effective in precisely cleaning damage-sensitive materials and enabling in situ hard-mask deposition[4,5].

This presentation demonstrates TAP's advantages in versatility, scalability, and precision over RIE and ALE for various materials and applications (Fig 2). TAP's sustainability benefits are demonstrated on CMOS BEOL stacks at 24 nm pitch. Additionally, patterning NbTiN/HfZrO/NbTiN capacitors and NbTiN interconnects for SQC at 28 nm pitch showcases TAP's superior pattern control. TAP also provides highly precise control over the etch rate of compound materials, as illustrated by the patterning of IGZO at a 28 nm pitch for 2T0C-based DRAM. The study is supported by plasma diagnostics (time-resolved measurements of ion, electron, and neutral density), highlighting the underlying plasma mechanisms, as well as electrical measurements demonstrating improved performance with TAP in patterning IGZO channels compared to RIE.

Compatible with as many materials as conventional etching, TAP not only provides better patterning performance and significantly lower consumption of harmful gases, but also achieves precision close to ALE, at a much higher throughput. This makes TAP a more sustainable and higher-performing solution for both current and future applications.

4:30pm **PS2-TuA-10 Fluorinated Gases in Plasma Etch: Challenges, Accomplishments, and Opportunities**, ***David Speed***, GlobalFoundries **INVITED**

Plasma etch and chamber clean processes are a primary source of CO_2-e emissions from semiconductor manufacturing processes. Net zero emissions and F-gas phase-out goals bring challenges that require multifaceted solutions, many of which have been the subject of industry efforts for over 30 years. This presentation surveys the principal challenges, accomplishments, and opportunities for achieving reduced CO_2-e emissions from plasma etch processes. Topics to be addressed will include etch process optimization, alternative low-GWP gases, enhanced abatement processes, gas capture and recovery, design integration strategies, and digital twin approaches.

5:00pm **PS2-TuA-12 Significance of the Impacts of Metal Oxide Resists (MORs) in Plasma Etch Processes**, ***Adam Pranda***, *Steven Grzeskowiak, Yusuke Yoshida, Eric Liu,* TEL Technology Center, America, LLC

One of the major developments in logic scaling has been the transition from 193nm deep ultraviolet (DUV) lithography to 13.5nm extreme ultraviolet (EUV) lithography. Historically, organic or chemically amplified resists (CARs) have been used for patterning because of sufficient radiation sensitivity, resolution, and etch resistance for enabling viable manufacturing flows with DUV lithography. However, the shift to EUV lithography presents numerous problems for CARs due to the reduced absorption of EUV light that among roughness and defectivity challenges also necessitates thinner resist thickness to achieve high resolution. For etch processes utilizing EUV CARs, this requires maintaining a sufficiently high etch selectivity to successfully transfer the pattern before integrity is lost. One approach to overcoming the challenges with CARs in EUV lithography has been the development of metal oxide resists (MORs), which demonstrate improved absorption of EUV light, improved etch resistance, and reduced line edge roughness. Given the significant difference in chemical properties between CAR and MOR, it is imperative for manufacturing viability to understand how existing etch processes are impacted by a switch to MOR in the patterning stack. In this study, we used a high-density plasma reactor to etch a benchmark blanket patterning stack (Fig. 1) containing either a EUV CAR or MOR. We utilized a characterization suite including optical emission spectroscopy (OES), spectroscopic ellipsometry (SE), atomic force microscopy (AFM), and x-ray photoelectron spectroscopy (XPS) to understand the relationships between the plasma conditions (OES), the evolution of the surface chemistry of the resists (XPS), and the resulting etch behavior (SE) and surface topography (AFM). The characteristic plasma processes for a patterned stack etch interact with MOR in a different manner than with CAR, resulting in different physical and chemical impacts to the resist itself, but also via etch byproducts alter the chamber condition and the etch behavior of subsequent etch steps in the patterning stack. We also applied the findings from the blanket stack work on patterned structures to investigate the impacts on pattern fidelity, especially since there is industrial interest to implement MOR for line-space patterning at pitch sizes of 32nm and below. Identifying the underlying mechanisms that lead to differences in the overall stack etch when MOR is used compared to CAR will provide key guidance into the development of process flows that integrate MOR.

5:15pm **PS2-TuA-13 Kinetic Study of Microwave-Powered, Atmospheric-Pressure Hydrogen Plasma Reduction of Iron Oxide**, ***Daniel Ellis***, *Vivek Pachchigar, Jazline Rebollar,* University of Illinois Urbana-Champaign; *Nabiel Abuyazid,* Lam Research Corporation; *Necip Üner,* Middle East Technical University, Turkey; *Ivan Shchelkanov,* Starfire Industries, LLC; *Brian Jurczyk,* Starfire Industries; *Jessica Krogstad, Mohan Sankaran,* University of Illinois Urbana-Champaign

The reduction of iron ore is a key step in steel production. There has been growing interest in applying plasmas to overcome thermodynamic and kinetic limitations with molecular hydrogen as a feedstock. Microwave excitation is of particular interest because of the potential to energy efficiently generate reactive plasma species. Previous studies have been carried out at low (vacuum) pressure or at high temperatures where the contribution of plasma species to the reduction process were not clear.

Here, we studied an atmospheric-pressure, microwave-powered hydrogen plasma for iron oxide reduction. By using a solid-state amplifier to generate the microwave power and a coaxial geometry to transmit the radiation and excite the gas, a plasma jet free from any surface is produced which can be used to treat a material downstream at low temperatures (<~400 ^{o}C). Using this setup, we treated thin films of iron oxide (hematite) powder to minimize diffusional resistance. The extent of reduction at various process conditions was evaluated by mass loss measurements and X-ray diffraction. The reduction was correlated with plasma properties by optical emission spectroscopy (OES). In particular, the density of hydrogen radicals in the plasma volume was obtained by actinometry and the transport of hydrogen radicals to the iron oxide surface was estimated by a one-dimensional diffusion-advection-recombination model. The surface temperature of the film was obtained by optical infrared pyrometry. All together, we were able to isolate the role of a plasma-activated species, the hydrogen radical, and demonstrate its capability for low-temperature reduction. In addition, a kinetic analysis was performed to obtain an apparent activation energy of ~50 kJ/mol, compared to purely thermal reduction of 92 kJ/mol.

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