Plasma Science and Technology
Room 315 - Session PS1-TuM

High Aspect Ratio and Cryogenic Etching I

Moderators: Prof. Kenji Ishikawa, Nagoya University, Japan, **Dr. Eric Miller**, IBM

8:00am **PS1-TuM-1 Challenges in Etching High Aspect Ratio Patterns for Memory Devices***, Seokhyun Lim, Wonbong Jung, In-Joong Kim, JungHwan Um,* ***Sung-Il Cho,*** Samsung Electronics Co., Republic of Korea **INVITED**

Since the first V-NAND was introduced in 2013, high aspect ratio contact(HARC) etching has become the most critical technology for developing 3D devices. As aspect ratio of vertical patterns increases, both profile fidelity and throughput become more demanding. Consequently, the etch-rate reduction known as aspect ratio dependent etching(ARDE) must be overcome first, and traditional development has focused on raising ion energy to meet this requirement. Recently, however, the requirement to minimize local variations, such as distorted patterns and abnormal critical dimensions, has grown substantially. For example, non-circular patterns in vertical-channel structures induce abnormal operation because of undesirable electric field distributions. This deformation is mainly caused by non-uniform polymer deposition and bent ion trajectories, which has led the semiconductor industry to adopt precise waveform control and polymer management technologies. Increasing ion energy, meanwhile, narrows the arcing margin of the equipment and raises charge-up damage concerns. The recently intorduced cryogenic etching can mitigate these problems associated with high bias power, but it brings its own set of requirements. At present, industrial cryogenic etching is limited to etch SiO2 and SiN selective to organic hardmasks. Therefore, a broader range of chemistries and plasma conditions should be exploited for various applications. In this presentation we will outline the various technical obstacles that arise in HARC etching and propose development directions to address them.

8:30am **PS1-TuM-3 High-Aspect-Ratio Carbon Hard-Mask Etch Using High-Density Plasma and a Novel Additive Gas Chemistry*, Koki Mukaiyama,*** *Shuji Funada, Ryusuke Seino, Maju Tomura, Yoshihide Kihara,* Tokyo Electron Miyagi Limited, Japan

In 3D NAND flash memory manufacturing, carbon is commonly used as a hard mask for channel-hole etching. As the number of stacked memory cells increases, the carbon mask must be made thicker, necessitating high-aspect-ratio (HAR) etching. Current carbon-mask etch processes employ oxygen with a sulfur-containing additive using high-density inductively coupled plasma (ICP) with high applied bias. Because sulfur-based sidewall protection becomes insufficient at high aspect ratios, process conditions that narrow the mask openings are often adopted to prevent enlargement of the critical dimensions (CDs). However, this narrowing restricts radical transport to the feature bottom, substantially reducing the etch rate in HAR regions. To address this issue, we focused on additive gas chemistry. Since the discovery of sulfur-containing additive gases [1,2], no additive gas that outperforms them has been reported. In this study, we introduced a novel additive gas (hereinafter referred to as “Gas A”) into oxygen plasma and evaluated its effects on etching characteristics. We found that Gas A reacts with carbon to form a passivation layer on the sidewalls even at high aspect ratios, yielding smaller hole CDs than those obtained with sulfur-based protection. In addition, Gas A removes deposits from the mask openings and suppresses CD narrowing at the openings during etch progression, while leaving the mask itself intact. Because fewer reactive species are consumed at the sidewalls and the mask openings remain larger, more radicals and ions can reach the HAR regions. As a result, the etch rate is enhanced while hole CDs are reduced. Furthermore, combining Gas A with sulfur-containing gases results in additional etch-rate enhancement and CD reduction. Using Gas A enables HAR etching of carbon masks thicker than 4 µm with feature diameters of approximately 100 nm.

[1] M. Pons *et al*., Jpn. J. Appl. Phys. 33 (1994).

[2] J. K. Kim *et al*., J. Vac. Sci. Technol. A 31 (2013).

8:45am **PS1-TuM-4 Passivation-less Etching in Cryogenic Regime*, Hiroto Ohtake*,** *Radhe Agarwal, Alvaro Garcia, Tina Dhekial-Phukan,* Applied Materials Inc.*; Han Luo,* Applied Materials Inc., Canada*; Jeong Hwan Kim, Teris Liu,* Applied Materials Inc.

As semiconductor devices continue scaling, feature dimensions have become increasingly narrow. These trends impose requirements on highly anisotropic etching in confined spaces. Conventionally, vertical etch profiles are achieved with passivation gases, such as oxidizing species, fluorocarbons, or oxygen halogenides, to suppress lateral etching of silicon. However, excessive passivation gas addition is causing etch stop or top clogging. Therefore, reducing or eliminating passivation gases is highly desirable.

Cryogenic etching technology might offer a promising path for passivation-less anisotropic etching. At cryogenic substrate temperatures, physisorption of reactive species is enhanced, while spontaneous chemical reactions are suppressed. As a result, a higher concentration of radicals can be delivered effectively to the etch front without excessive lateral attack. But high pressure and high source power impact the sidewall etch even at cryogenic temperature.

In this study, plasma operation at low pressure (0.5 mTorr) and low RF power (50 W) with cryogenic substrate temperature was stabilized in a 300 mm diameter etching chamber through optimization of the coil and top structure. To validate the concept, carbon etching was employed as a model. Under low-pressure and low-power conditions, the ion-to-radical flux ratio increases, enabling directional etching even in a pure oxygen plasma without passivation additives. By lowering the substrate temperature from −40 °C to −90 °C, the ratio of vertical to lateral carbon etch rates improved substantially from 2.8 to 7.2. This indicates that spontaneous reactions are significantly reduced at cryogenic temperatures, allowing the formation of anisotropic profiles with reducing the use of passivation gases. The anisotropy was also found to be sensitive to process pressure. At −90 °C, the vertical-to-lateral etch rate ratio decreased to 3.7 when the pressure was increased to 10 mTorr. Plasma simulations indicate that lower pressures yield a higher ion-to-radical ratio, which directly contributes to enhanced anisotropy.

In conclusion, cryogenic etching under low-pressure and low-power conditions might be a promising approach for next-generation semiconductor etching, enabling highly anisotropic profiles with less passivation chemistries.

9:00am **PS1-TuM-5 The Evolution of CVD-C Mask Profile During High-Aspect-Ratio Hole Etching*, Mitsuhiro Omura*,** *Li Wu, Junichi Hashimoto, Chihiro Sakamoto, Chihiro Abe, Yuta Manabe, Hirotaka Tsuda, Toshiyuki Sasaki,* KIOXIA, Japan

The advent of AI has increased the importance of semiconductor devices in modern technology. New generations of 3D flash memory have joined logic devices and DRAM as key components enabling this new era. To meet the increasing bit density demand, flash devices incorporate an ever-increasing number of word lines. These, in turn, complicate the dry etching of memory holes, which form the space for channels and functional thin films. This high-aspect-ratio memory hole etching process requires precise profile control, with challenges such as low mask selectivity, necking, clogging, bowing, striation, hole bottom distortion, etc[1].

Here, we focus on the issue of mask sidewall encroachment known as ‘necking’. The mechanism behind this effect has been simulated by considering polymer deposition from neutrals and ion sputtering using a vertical cross section perspective [2]. In this analysis, we turn our attention to the neck shape revealed in the less understood horizontal cross section. We began by etching a typical SiO/SiN film stack in a fluorocarbon-mixed gas plasma. The test structure also contained a CVD-deposited carbon (CVD-C) hard-mask with a dense hole pattern. We then observed the neck shape on the CVD-C mask in a horizontal cross section for two types of hole patterns in equilateral and isosceles triangle arrangements. Distortion in the isosceles triangles far exceeded that shown in the equilateral triangles despite identical processing conditions. By observing the evolution of mask surface morphology, we find that early local mask erosion at the narrower hole-to-hole spaces in the isosceles triangle arrangement eventually leads to significant variation in the mask height remaining. This variation might lead to neck profile variation such as height, width, and taper angle in a vertical cross section. We speculate that variation in the remaining height of the CVD-C mask could lead to inconsistent neck profiles which manifest in the horizontal cross sections as hole distortion.

References

[1] G. S. Oehrlein et al., J. Vac. Sci. Technol. B 42(4), 041501 (2024).

[2] D. Kim et al., Thin Solid Films 515, 4874 (2007).

9:15am **PS1-TuM-6 ASSD Student Award Finalist Talk: Plasma Chemistry and Cryogenic Control of Etching, Passivation, and Surface Modification in Hydrogenated Amorphous Carbon Thin Films***, **Jhonatan Gil Romero**, Kenneth Lathrum, Seonhee Jang,* University of Louisiana

Hydrogenated amorphous carbon (a-C:H) is used as a hard-mask material for semiconductor patterning, which requires a precise balance between etch rate, passivation, surface roughness, wettability, optical response and oxide/a-C:H selectivity. This work maps how plasma chemistry, cryogenic temperatures, inductively coupled plasma (ICP) and radio frequency (RF) power in the etching process tune these coupled responses.

a-C:H films were deposited on Si (100) by plasma-enhanced chemical vapor deposition (PECVD) using a cyclohexane precursor at room temperature. They were processed in an inductively coupled plasma deep reactive ion etching (ICP-DRIE) system under RF-only or ICP+RF power modes. Four primary fluorine gases (SF_6, CF_4, CHF_3, and C_4F_8) and three secondary gases (O_2, Ar, and N_2) were evaluated across temperatures between -120 and 20 °C and pressures between 3.333 and 9.999 Pa. Film thickness and optical constants were measured by ellipsometry, surface morphology and roughness by atomic force microscopy (AFM), and wettability by a contact-angle goniometer. Tetraethyl orthosilicate (TEOS) oxide was used to determine TEOS/a-C etch selectivity, calculated when both films had positive net etch rates.

Under fixed ICP+RF power, gas chemistry controlled the transition between film removal and passivation. Oxygen (O_2) containing mixtures yielded the highest etch rates, led by CF_4+O_2 at median 2.43 nm/s versus 1.03 nm/s for CF_4. Fluorocarbon-rich chemistries suppressed etching or promoted net film growth: CF_4+CHF_3 yielded the lowest median etch rate at 0.10 nm/s, while C_4F_8 and CF_4+C_4F_8 showed median growth rates of 1.12 and 0.562 nm/s. Cryogenic conditions (-30 to -120 °C) increased median passivation growth relative to 20 °C by 84% for CF_4+C_4F_8. Under ICP+RF, C_4F_8 passivation also increased root mean square (RMS) roughness by 140%, relative to CF_4 at 0.1834 nm. Passivation further increased hydrophobicity, with median change in contact angle (ΔCA) up to +6.94°. In contrast, O_2-assisted etching produced hydrophilic surfaces, with median ΔCA reaching -33.1° for RF-only CF_4+O_2. The highest selectivity value was 2.740 for CF_4+CHF_3 under ICP+RF. ICP+RF power enhanced a-C:H removal in 13/16 paired (RF-only) comparisons; lowering pressure increased ICP+RF etch rate but reduced selectivity by 28%. Optically, passivation increased the final extinction coefficient by 33.5%, and CF_4+O_2 etching by 67.6% relative to CF_4.

These results define the process windows for O_2-assisted a-C:H removal, fluorocarbon passivation, and pressure/power tradeoffs, providing a framework for balancing TEOS/a-C selectivity, surface properties, and optical response in advanced patterning.

9:30am **PS1-TuM-7 Characterizing Spontaneous Etching of Si_3N_4 Sidewalls in Ar/Fluorinated Precursor Plasmas Using a Small-Gap Structure: Role of Precursor and Substrate Temperature***, **Md Intaqer Arafat**,* University of Maryland College Park*; Pierre Ricou, Behnaz Ghaffari, Jessica DeMott,* Arkema Inc*; Gottlieb S. Oehrlein,* University of Maryland College Park

High-aspect-ratio (HAR) etching of ONO stacks for 3D–NAND is challenging due to profile defects and non-uniform selectivity; fluorinated precursors control etch and passivation, but the underlying plasma–surface mechanisms remain unclear. This study investigates a series of $C_2H_{5-x}F_{1+x}$ precursor candidates in low-pressure plasma, focusing on their deposition behavior and impact on isotropic etching (sidewall) of HAR structures. Key parameters include hydrofluorocarbon (HFC) film deposition rate, film properties, etch rate, and the degree of sidewall etching of silicon nitride (Si_3N_4), all evaluated as functions of precursor composition. To mimic HAR conditions, horizontal trench structures with aspect ratios (AR) up to 30 were used to examine the role of neutral radicals generated from $C_2H_{5-x}F_{1+x}$ plasmas. Nitride trenches were processed by inductively coupled plasma, with spatial analysis via ex situ ellipsometry and real-time ellipsometry on blanket films. Findings reveal systematic variations in the film deposition rate, refractive index, and sidewall etching behavior, with notable changes in spontaneous etching of Si_3N_4 observed for different $C_2H_{5-x}F_{1+x}$ precursors. Increasing fluorine content within the C_2 precursor family enhances deposition rates and reduces refractive index. At the same time, spontaneous etching of Si_3N_4 becomes more pronounced, particularly near trench entrances. For fluorine-rich precursors with H/F < 1, this etching extends further into HAR features, suggesting deeper penetration of reactive species. Experiments were conducted at substrate temperatures of 10 °C and –45 °C to examine sidewall etching. Lowering the substrate temperature from 10 °C to −45 °C significantly reduces Si_3N_4 sidewall etching. This reduction is accompanied by decreases in both HFC deposition rate and refractive index compared to 10 °C, indicating modified film growth characteristics. Additionally, operation at −45 °C limits the penetration of fluorine and carbon species into HAR structures and reduces the formation of fluorinated nitride. These results suggest viable strategies in which the chemical characteristics of the precursor are leveraged to control the balance between protective passivation and chemical removal on vertical surfaces during HAR etching, enabling improved precision in etching processes.

This material is based upon work supported by Arkema, USA.

9:45am **PS1-TuM-8 Effect of Substrate Temperature on Neutral Species Transport in High-Aspect-Ratio Holes During Plasma Etching***, **Yusuke Imai**, Takayoshi Tsutsumi, Sekine Makoto, Kenichi Inoue, Kenji Ishikawa,* Nagoya University, Japan

The continued scaling and three-dimensional integration of semiconductor devices have significantly increased the complexity of plasma etching processes. In advanced device fabrication, such as high-aspect-ratio (HAR) patterning for 3D NAND structures, highly anisotropic and precisely controlled etching is required. Substrate temperature is one of the key parameters governing etching characteristics and is carefully controlled during the etching process. Recently, it has been reported that lowering the substrate temperature enables faster and deeper etching in HAR processing for 3D NAND fabrication compared with conventional processes. [1] Substrate temperature is considered to play an important role not only in surface reactions during etching but also in neutral species transport [2]; however, its influence has not yet been fully understood.

In this study, we investigated the effect of substrate temperature on neutral species transport in HAR holes using a quadrupole mass spectrometer (QMS). A cylindrical orifice mimicking a HAR hole was installed at the inlet of the QMS, enabling aspect-ratio-resolved mass spectrometry (ARMS). In addition, a temperature-controlled assembly was mounted around the orifice to control the orifice temperature during measurements. Neutral species transport through the HAR hole was investigated while varying the orifice temperature. The experiments were performed using a capacitively coupled plasma (CCP) reactor. RF power at 13.56 MHz was applied to the upper electrode, while argon and fluorocarbon gases were introduced into the reactor, where the pressure was maintained at 2 Pa.

As the orifice temperature decreased, the measured Ar intensity increased. This behavior is considered to originate from a reduction in the local gas temperature near the cooled structure, resulting in an increase in neutral gas density and flux into the orifice. These results suggest that low-temperature conditions during plasma etching may enhance the neutral species flux entering HAR features.

[1] R. Suda et al., J. Vac. Sci. Technol. B 43, 062210 (2025).[2] T. Lill et al., J. Vac. Sci. Technol. A 41, 023005 (2023).

Author Index

Bold page numbers indicate presenter

— A —
Abe, Chihiro: PS1-TuM-5, 1
Agarwal, Radhe: PS1-TuM-4, 1
Arafat, Md Intaqer: PS1-TuM-7, **2**
— C —
Cho, Sung-Il: PS1-TuM-1, **1**
— D —
DeMott, Jessica: PS1-TuM-7, 2
Dhekial-Phukan, Tina: PS1-TuM-4, 1
— F —
Funada, Shuji: PS1-TuM-3, 1
— G —
Garcia, Alvaro: PS1-TuM-4, 1
Ghaffari, Behnaz: PS1-TuM-7, 2
Gil Romero, Jhonatan: PS1-TuM-6, **2**
— H —
Hashimoto, Junichi: PS1-TuM-5, 1
— I —
Imai, Yusuke: PS1-TuM-8, **2**
Inoue, Kenichi: PS1-TuM-8, 2
Ishikawa, Kenji: PS1-TuM-8, 2
— J —
Jang, Seonhee: PS1-TuM-6, 2
Jung, Wonbong: PS1-TuM-1, 1
— K —
Kihara, Yoshihide: PS1-TuM-3, 1
Kim, In-Joong: PS1-TuM-1, 1
Kim, Jeong Hwan: PS1-TuM-4, 1
— L —
Lathrum, Kenneth: PS1-TuM-6, 2
Lim, Seokhyun: PS1-TuM-1, 1
Liu, Teris: PS1-TuM-4, 1
Luo, Han: PS1-TuM-4, 1
— M —
Makoto, Sekine: PS1-TuM-8, 2
Manabe, Yuta: PS1-TuM-5, 1
Mukaiyama, Koki: PS1-TuM-3, **1**
— O —
Oehrlein, Gottlieb S.: PS1-TuM-7, 2
Ohtake, Hiroto: PS1-TuM-4, **1**
Omura, Mitsuhiro: PS1-TuM-5, **1**
— R —
Ricou, Pierre: PS1-TuM-7, 2
— S —
Sakamoto, Chihiro: PS1-TuM-5, 1
Sasaki, Toshiyuki: PS1-TuM-5, 1
Seino, Ryusuke: PS1-TuM-3, 1
— T —
Tomura, Maju: PS1-TuM-3, 1
Tsuda, Hirotaka: PS1-TuM-5, 1
Tsutsumi, Takayoshi: PS1-TuM-8, 2
— U —
Um, JungHwan: PS1-TuM-1, 1
— W —
Wu, Li: PS1-TuM-5, 1