Induced Chemical Networking of Organometallic Tin in a Cyclic Framework for Sub-10 nm Patterning and Interconnect Application

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revealed the formation of Sn–O–Sn and Sn–OH networks along with the loss of carbon-based group(s) upon radiation exposure, resulting in the generation of insoluble products in the exposed region, which becomes the basis of polarity switching and hence pattern development. The resist was found to have good etch resistance with respect to silicon. Moreover, Sn–CT has been explored as a good gap-filling material for silicon (Si) front-end devices and interconnects due to its low- κ dielectric (~1.9) and high diffusion barrier properties.

KEYWORDS: organotin resist, nanolithography, sub-10 nm patterns, pattern transfer, low- κ dielectric

INTRODUCTION

Reduction in the transistor size in advanced electronic devices is highly essential in view of the current demand of the semiconductor market.^{1,2} In this regard, nanolithography has been proven to be an indispensable technique for high-volume production of nanochips.^{3–8} It plays an important role in advancing next-generation integrated circuit (IC) chip fabrication. Recent chip fabrication technology is progressing toward the fabrication of 5 nm node or below with the help of extreme ultraviolet lithography (EUVL).9 Hence, the era demands single-nanometer technological nodes which further require suitable resist materials that can print features at sub-10 nm regime through a single exposure, although their development is truly challenging.^{10–15} In recent times, resist compositions comprising inorganic or organometallic species with resolution potential at the single-nanometer regime and high etch resistance capabilities even with thickness below 20 nm have drawn special attention.¹³⁻¹⁵ For sub-10 nm patterning applications, it is desirable that the film thickness should be less than 20 nm to avoid pattern collapse.^{7,8} Also, developing an understanding of the mechanistic aspect of polarity switching of inorganic resist during exposure is an important area as it helps in designing new resist platforms

with better performance at a single nanometer regime.^{15–20} Among various types of inorganic resists, some tin-based compositions are being considered to have the potential to meet the current demand.^{11,19,21–26} In reality, some spin-on type tin-based inorganic resist formulations have been proven to have potential for advanced node applications.^{27,28} Moreover, as per the recent developments, a few inorganic resists have been shown to have true potential for patterning at a single nanometer regime with a very good pattern profile.^{9–13} However, the number of such materials is truly limited. Herein, we demonstrate the potential of an organotin-based cage-like network $(Sn-CT)^{29}$ as an inorganic resist system for sub-10 nm patterning (Figure 1). In general, at the developmental phase, the resists for EUVL are often screened initially with electron beam lithography (EBL) and helium ion beam

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Figure 1. Schematic of lithography process flow and performed micro/nanopattern formation on the silicon substrate. Sn-CT: Molecular structure of the cyclic organotin-based resist.

lithography (HIBL) to evaluate the patterning potential. $^{21-26,30-48}$

While the market of semiconductor industries is skyrocketing, the need for resist compositions for low-cost and efficient patterning of advanced node device architecture, particularly nanopatterning at a single nanometer regime, is quite evident.^{3,4} Owing to their importance in specialized applications, the cells of memory devices need complex metal interconnect features.⁴⁹

It is to be noted that the fabrication of advanced CMOS devices involves complex processes, wide-ranging advanced materials, and technologies, particularly considering current trends and market demand. In this line, low- κ dielectric gap-filling materials for interconnect applications are very important.^{50–52} In modern CMOS circuits, parasitics from interconnects pertaining to the resistance-capacitance (RC) delays and crosstalk reduction between multilevel interconnects are increasingly becoming important to achieve higher speed and lesser power consumption.⁵⁰ Hence, novel alternate interlayer dielectric (ILD) materials, compatible with low resistivity copper (Cu) interconnects must be explored for the next-generation (NG) technology nodes.⁵³

Herein, we present the experimental results on Sn-CT as high-resolution resist with successful patterning of ~15 nm dense (line/space) features as well as patterns with ~ 8 nm critical dimension (CD) at an EBL dose of 2.5 mC/cm². Furthermore, we have successfully patterned ~15 nm dense features (line/space) as well as ~ 10 nm line features at a low dose of 16 $\mu \bar{C}/cm^2$ using HIBL. Given the importance of complex nanofeatures for specialized applications such as hard mask fabrication for lithography, nanoelectronic devices, photonic devices, and bit-patterned media for high-density recording,^{21,30,54-56} Sn-CT has been explored for patterning various complex features at a sub-10 nm regime including a real-scaled device design⁴⁹ with \sim 7 nm CD. In addition, we investigated using XPS spectroscopy the possible mechanism of polarity switching of Sn-CT during exposure.⁵⁷⁻⁶⁰ Sn-CT showed good etch resistance as compared to silicon and has been used for pattern transfer at the nano-regime. With the promising outcome from the nanopatterning experiments using the Sn-CT resist, we investigated its potential to be used as a low- κ dielectric gap-filling material for device interconnect applications. Interestingly, the exposed Sn-CT showed very good dielectric properties with $\kappa = \sim 1.9$ (100 to 500 kHz) measured by metal oxide semiconductor (MOS) CV characterization. Hence, Sn-CT can be used as a promising material for dual application in manufacturing electronic devices with advanced nodes.

RESULTS AND DISCUSSION

Sn–CT was synthesized following a modified literature procedure (see ESI for details).²⁹ The formed Sn–CT cage was characterized by nuclear magnetic resonance (NMR) and Fourier transform infrared (FTIR) spectroscopies. In FTIR, it showed peaks at 3030 (Ar–H), 2961 (C–H), 1620 (aromatic), 1590 (carbonyl), 1536 (aromatic), 1408 (carbonyl), 615 (O–Sn–O), 590 (Sn–O), and 532 (Sn–C) cm⁻¹. All characterization details are provided in the Supporting Information. The compound Sn–CT showed good thermal stability as established from thermogravimetric (TGA) and differential scanning calorimetric (DSC) analyses. The Sn–CT was stable up to ~260 °C whereas DSC analysis showed a melting temperature at 256 °C (Figure S1a,b).

After the complete characterization of Sn-CT, we started investigating its film-forming and patterning potential. To start with, the thin film of Sn-CT was spin-coated on the p-type silicon (100) wafer substrate, and then, the thin film characteristics were studied. The smooth and defect-free thin film of Sn-CT was observed under an optical microscope (Figure S2a) which was also supported by its AFM image (Figure S2b,d-f). The calculated root means square (RMS) value supported ($R_q = 0.84$ nm) the formation of the smooth film. The thin film of Sn-CT was then exposed to deep ultraviolet lamp (DUV; $\lambda = \sim 254$ nm) with a power of ~ 1 mW/cm^2 for 4 min (~240 mJ/cm²) followed by post-exposure bake at 110 °C for 90 s. Then, the patterns were developed using a combination of methyl isobutyl ketone (MIBK): isopropyl alcohol (IPA) (3:1) as the developer. After that, the patterns were studied under an optical microscope and AFM (Figure S2c,g-j). The optical image of developed negative tone patterns depicted the formation of patterns (line and square patterns) with line widths of \sim 3–15 µm. Sn–CT showed negative tone resist characteristics under DUV irradiation (Figure S2h-j) which encouraged us to further explore Sn-CT as a resist material for advanced nanolithography applications. However, before moving to nanolithography applications, we intended to gain insights into the mechanistic aspects of polarity switching upon exposure to radiation which becomes the basis for negative tone pattern development.

Mechanistic Study for Pattern Formation. Given the promising potential of Sn–CT as a resist material, we adopted

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Figure 2. High-resolution XPS data for C 1s, O 1s, and Sn 3d; (a-c) before exposure; (d-f) after exposure.

X-ray photoemission spectroscopy (XPS) to analyze the thin films of Sn-CT before and after exposure for mechanistic investigation. After spin coating the thin film of Sn-CT (thickness ~20 nm) on the silicon surface, the film was floodexposed with DUV photons (~254 nm) and subjected to X-ray spectroscopy. In C 1s spectra, as shown in Figure 2, we found that the most intense component at 284.8 eV corresponds to carbons (butyl groups and aromatic carbons) in Sn-CT. Other components were found at 286.6 and 288.8 eV which correspond to C–O and –COOH carbons. After the DUV (λ = \sim 254 nm) exposure (dose \sim 300 mJ/cm²), a decrease in the intensity of the peak at 284.8 eV was noticed, and at the same time, the peaks for C-O and -COOH carbon showed little enhancement in their peak intensities (Figure 2). It has been established earlier that the Sn-C bond dissociates homolytically upon radiation exposure and suffers oxidation in the presence of atmospheric oxygen. $^{57-59}$ Thus, the decrease in intensity of the peak at 284.8 eV could be attributed to carbon loss while the corresponding increase in C-O and COOH carbons is due to the further oxidation of the dissociated carbon chain species.

The O 1s spectra of the unexposed Sn–CT film showed two components at 532.2 and 533.9 eV, which were accredited to the Sn–OOC/OC group and OH/moisture.^{57,58,60,61} After exposure, the overall increase in peak intensity could be ascribed to the additional formation of Sn–OH groups and Sn–O–Sn linkage. As stated above, after the carbon loss, the bare Sn will get oxidized to Sn–OH species; however, the condensation of some of the Sn–OH groups to Sn–O–Sn is highly possible.⁵⁷ To get a deeper insight, the O 1s peak was deconvoluted into three components evidencing Sn–O–Sn/Sn–OH (531.2 eV), Sn–OOC/O–C (532.4 eV), and OH/ moisture groups (534.0 eV).^{60,61} An increase in the formation of the Sn–O–Sn network upon radiation exposure was also evident from the solubility transition of the Sn–CT film to insoluble hardened film.

The major effect was observed in the Sn 3d spectra where the spin-orbit-spin doublet for Sn 3d5/2 (487.1 eV) and Sn $3d_{3/2}$ (495.5 eV) showed a shift to higher binding energies (BE), 487.5 and 495.9 eV, respectively. The shift in BE and intensity for Sn doublets could be related to the change in the environment of Sn species present in the sample after irradiation. Additionally, the appreciable increase in the intensity of Sn 3d peaks was possibly because of reduction in attenuation from tin sites that were formed after the loss of the butyl group (Figure 2).^{19,57–59} The appearance of shake-up satellite peaks has been discussed in the literature for electron transition to unoccupied orbitals/bands from occupied orbitals/bands.⁶² It could be assumed that in molecular complex Sn-CT, which is composed of aromatic units, these satellite peaks for electron transition between occupied and unoccupied orbitals are observed. Upon irradiation, as Sn-CT underwent structural changes, the molecular orbital structure will also change. These structural changes might have led to the disappearance of satellite shake-up peaks.

We have quantified the atomic composition of Sn-CT before and after radiation exposure. The atomic percentage (At. %) of carbon exhibited a noticeable decrease from ~70 to ~55%, which has been attributed to the butyl group loss, whereas, a corresponding increase in O (~25 to ~36%) and Sn (~5 to ~9%) was noted. The observable enhancement in the Sn content signified the metal densification which helped to obtain solubility transition properties by the Sn-CT film. All these results allowed us to understand the solubility transition of Sn-CT upon radiation exposure. These observations have been presented in Figure S3 as a possible mechanism of polarity switching mainly due to induced controlled densification leading to the formation of an insoluble Sn-O network resulting in a negative tone pattern.

Evaluation of Resist Sensitivity and Contrast in EBL. Next, the spin-coated thin films (thickness \sim 15 nm) of Sn–CT were exposed to various doses of e-beam radiation from 0.01–



Figure 3. Patterning with Sn–CT using EBL: (a) FE-SEM images with characteristics of ~15 nm (L/S); (b) ~20 nm (L/S); (c) mesh with ~14 nm width; (d) and (e) ~25 nm and ~7 nm device-like designs, respectively, and (f) ~11 nm nanopillar/dot arrays.

3 mC/cm² followed by a postexposure bake at 110 °C for 90 s. E-beam sensitivity (10–28 keV) of the Sn–CT resist was evaluated by analyzing the developed square patterns using AFM/SEM techniques. The sensitivity was evaluated from the response graph (at half the normalized thickness, $D_{0.5}$) (Figure S4) and calculated to be 0.8 mC/cm² (10 keV), 1.5 mC/cm² (20 keV), and 1.9 mC/cm² (28 keV) with the contrast of 1.79 (10 keV), 1.83 (20 keV), and 2.33 (at 28 keV), respectively.

The patterning capability was evaluated through line-andspace (L/S) patterning where \sim 15 nm and \sim 20 nm half-pitch dense patterns (~15 nm, ~20 nm L/S) were obtained (28 keV, dose 2.5 mC/cm²) (Figure 3a,b). It was observed that Sn-CT is also capable of patterning complex mesh patterns with line widths of ~ 14 nm (dose 2.5 mC/cm²) (Figure 3c). Apart from this, isolated ~ 9 nm line patterns and ~ 14 nm L/ 2S patterns were obtained (Figure S5). To ascertain the potential of Sn-CT as a resist material, complex patterns were further developed. Owing to their importance in specialized applications, the cells of memory devices need complex metal interconnect features.⁴⁹ We successfully demonstrated the nanoprinting of device-like architecture, both at single and double-digit regimes, on silicon surfaces using the Sn-CT resist. The prototype patterns were analyzed by SEM imaging which showed a line width of $\sim 25 \text{ nm} (4 \text{ mC/cm}^2)$ (Figure 3d). Similarly, a device-like design with \sim 7 nm (4 mC/cm²) line width was also fabricated using Sn-CT (Figure 3e) upon single exposure. Additionally, an array of nanopillar (11 nm diameter nanopillar/dot arrays and ~22 nm half-pitch with dose energy 3.3 mC/cm²) features was developed (Figures 3f, S5c). Moreover, additional complex features such as ~8 nm elbow patterns (dose 3.3 mC/cm^2), ~9 nm mesh grid, circular grating with different width patterns, and starlike patterns were developed on a silicon substrate (Figure S6). AFM images also supported the formation of patterns (Figure S7). The LER/ LWR for ~15 nm isolated line patterns were calculated and found to be within the range of 1.8/2.8 nm. (Figure S8).

High-Resolution Pattern Development Using Helium Ion Beam Irradiation. Furthermore, the patterning advancement of the resist material was probed under a helium ion beam (HIB, 25 keV). To determine the sensitivity of the resist film, an array of 500 × 500 nm squares was patterned with a variable dose array of HIB, and the developed patterns were studied by SEM and AFM techniques. The sensitivity of the resist at $D_{0.5}$ was 4.8 μ C/cm² with a contrast (γ) of 1.85 (Figure S9). The sensitivity data indicated that higher dose energy may be required to obtain defect-free patterns. The L/S features were patterned using very thin resist film (~15 nm film thickness) and a combination of methyl isobutyl ketone (MIBK)–isopropyl alcohol (IPA) (3:1) was used as a developer. High-resolution SEM images of the formed patterns have been shown in Figure 4. To further evaluate the potential



Figure 4. Patterning of Sn–CT under HIBL: (a) FE-SEM images of ~15 nm (L/S), (b) ~18 nm (L/S), (c) ~14 nm (L/2S), and (d) ~10 nm (L/4S) features.

of Sn–CT, L/S patterns of different sizes such as \sim 15 nm and \sim 18 nm L/S as well as patterns of different line/spaces such as \sim 14 nm L/2S and \sim 10 nm L/4S were printed on the silicon surface (Figure 4) using the HIBL technique.

Pattern Transfer Study. Transfer of printed patterns on silicon surfaces with the help of a suitable etch recipe to establish the real potential of a resist composition for practical

application is very important in the area of resist technology. The developed patterns (SEM and AFM images of ~50 nm isolated lines patterns, Figure S10) were subjected to RIE etch for 150 s (sulfur hexafluoride (SF6) @22 sccm, 40 W RF power at 15 mT chamber pressure) and AFM images were captured to analyze the etch potential. The resulting silicon fins had an average width of ~50 nm and an average height of ~90 nm (Figure 5). The effective etch rates were calculated for



Figure 5. Morphology of the transferred pattern using Sn-CT resist: (a) AFM image of ~50 nm etched patterns; (b) 3D-AFM image of ~50 nm etched patterns.

silicon and Sn–CT to be ~0.6 and ~0.14 nm/s, respectively. It is thus clear that the resist material remained as a hard mask on the top layer of the silicon structures, and hence, successful pattern transfer was possible (Figure 5).

Low- κ **Behavior Study.** Next, we became interested in investigating if Sn–CT can be used as a low- κ dielectric gapfilling material for device interconnect applications. In this regard, metal–organic materials have been found to have the potential to act as interconnect materials due to their considerable low- κ dielectric constant (κ < 2.5) and compatibility with CMOS processing.⁵⁰ Given the possibility of metal–organic materials for such applications, Sn–CT has been explored as an interlayer dielectric for NG applications due to its significantly low Cu diffusivity and dielectric constant for interconnect applications.

To examine the thin Cu layer degradation, a thin (20 nm) layer of Cu was deposited on Sn-CT (40 nm)/p-Si and p-Si (reference sample), and sheet resistance change was measured w.r.t. the reference sample at different temperatures. It is evident from Figure 6a that the sheet resistance of Cu/Sn-CT/p-Si and Cu/p-Si samples is stable up to 100 $^{\circ}$ C, and the sheet resistance change in the Cu/Si sample is remarkably high



Figure 6. Sn-CT resist: (a) Normalized sheet resistance R(T)/R (25 °C), where R(T) is the measured sheet resistance at temperature (*T*), and *R* (25 °C) is the measured sheet resistance at 25 °C of Cu/Sn-CT/p-Si stack in comparison with Cu/p-Si at different temperatures along with the measurement setup schematic (inset), (b) temperature-dependent current density vs voltage, dielectric constant (κ) vs frequency spectra (inset) for Al/Sn-CT/p-Si MOS devices.

at 150 °C. This indicates that the thin Cu layer is degraded and diffused into the underlying structure. In the Sn–CT sample, sheet resistance variation was 60% less as compared to the Cu/Si sample at 175 °C. This is attributed to the Sn–CT acting as the barrier to Cu diffusion, thus avoiding Cu degradation up to 175 °C.

Next, we intended to verify the electrical barrier properties at elevated temperatures. Hence, the Sn-CT formulation was spin-coated on standard RCA cleaned p-Si wafers. The spincoated film was subjected to a pre-exposure bake at 95 °C for 60 s followed by UV flood exposure for 5 min (\sim 300 mJ/cm²) followed by hard baking at 130 °C for 5 min which possibly led to cross-linking of samples in the exposed area and resulting in the formation of insoluble Sn-O-Sn network. After crosslinking of resist, the Cu gate electrode was fabricated by using a metal shadow mask. Thereafter, IV measurements were performed between Cu/Sn-CT(ILD)/p-Si, as shown in Figure 6b. The IV measurement was carried out at different temperatures starting from room temperature to 175 °C. It is observed that the leakage current density was significantly reduced after sandwiching the Sn-CT and the leakage current density was measured (~100 μ A/cm²) at 100 °C at a gate voltage of 1 V, which is a noteworthy low current density as compared to normal Cu/p-Si IV measurement. Apart from it, no breakdown of Sn-CT was observed till 175 °C with voltage swept up to 5 V s. For I-V comparison, another set of reference samples was fabricated with Cu directly deposited on p-Si (see Supporting Information Figure S11). Validation of low leakage current is not sole enough to utilize the formulation for Cu interconnect applications. Therefore, the dielectric constant (κ) of the Sn-CT formulation was measured. The metaloxide-semiconductor (MOS) structures were fabricated on RCA cleaned Si wafers. The aluminum gate electrode was fabricated by using a metal shadow mask through thermal evaporation. The low polarizability of the Sn-CT bonds in the cross-linked framework directly relates to their dielectric constant. The dielectric constant was measured from 10 kHz to 1 MHz (κ value ~1.8 to ~2.2), with a minimal frequency dispersion, as depicted in the inset of Figure 6b. However, the κ value is consistent at ~1.9 in the range of 100 to 500 kHz, and the κ value <2.5 was measured overall. The variability of the κ value is attributed to the intrinsic (dielectric relaxation) and extrinsic (parasitic effects) causes.^{63,64} As evident from the literature, Sn-CT can be considered among those which are known as an efficient low- κ dielectric gap-filling material for device interconnect applications (Figure S12).

Together, along with its promising potential to act as a resist for sub-10 nm patterning including printing of complex devicelike design at a single nanometer regime, Sn–CT can also be used as an efficient gap-filling low- κ dielectric material for interconnect applications, indicating its capability for important dual applications in the area of semiconductor fabrication.

CONCLUSIONS

To conclude, the propensity toward densification under radiation (photon/e-beam/helium ion beam) exposure was explored to utilize an organometallic tin-based cyclic molecular cage compound (Sn-CT) as a negative tone resist material for nanopatterning, particularly at a single nanometer regime. It was established through mechanistic study on the single dose DUV light exposed thin film of Sn-CT using XPS that the simultaneous loss of the butyl group and the formation of Sn-O-Sn as well as the Sn-OH network led to the densification of the resist in the exposed region, resulting in the formation of insoluble products (under the developing condition) which becomes the basis of polarity switching. We successfully patterned dense (L/S) as well as isolated features using EBL or HIBL techniques. We patterned ~20/~18/~15 nm L/S features, ~8 nm mesh structures, ~9 nm isolated lines, and many other different types of complex features. Moreover, we could pattern a memory device-like design with \sim 7 nm line width upon single exposure. Also, the resist showed good etch resistance with respect to silicon. In addition, we have shown pattern transfer of ~50 nm patterns on the silicon surface. All these indicate the capability of Sn-CT to act as a resist for nanolithography with practical applications. Moreover, not only its promising nanopatterning potential, we also have experimentally established that Sn-CT can be used as an efficient low- κ dielectric gap-filling material for interconnect device applications. Thus, Sn-CT has been investigated to have a strong footing as a single material with two important applications in semiconductor fabrication, both as resist and low- κ dielectric gap-filling materials.

MATERIALS AND METHODS

Materials. 5-Hydroxyisophthalic acid, dibutyltin dichloride, and propylene glycol methyl ether acetate (PGMEA) were purchased from TCI chemicals. Methanol, isopropyl alcohol (IPA), and methyl isobutyl ketone (MIBK) were purchased from Merck. Silicon wafers were purchased from the Wafer World. All the materials were used without any purification.

Material Characterization. NMR (Jeol-500 MHz) and FTIR spectroscopy (Agilent carry 600) were used to characterize the synthesized molecules. Thin films were examined by AFM (Dimension Icon, Bruker) and field emission scanning electron microscopy (FE-SEM, Gemini SEM 500, Zeiss, Germany) for surface roughness and morphology. TGA and DSC (STA 449 F1 Jupiter, NETZSCH) were performed in a nitrogen atmosphere at a scan rate of 5 °C min⁻¹. XPS was used to examine the chemical and electronic states of Sn–CT (XPS, Nexsa base, Thermo Fisher Scientific).

Thin-Film Preparation. The freshly prepared solid powder sample (20 mg) of Sn–CT was dissolved in 1 mL of PGMEA using a vortex mixing for 10 min to ensure the powder is soluble in PGMEA. The resulting solution was filtered using a syringe filter (0.22 μ m) to obtain a clean solution of Sn–CT. The solution was then spin-coated on a silicon wafer (~2 × 2 cm²) using a spin coater (Laurell instrument, WS-650MZ-23NPPB).

Lithography Sample Preparation. All samples for electron beam lithography were coated on p-type silicon wafers ($\sim 2 \times 2 \text{ cm}^2$). Silicon wafers were initially cleaned with ultrasonic wash in acetone (15 min), methanol (15 min), and finally in IPA (15 min). Then, nitrogen gas was used to dry the substrates. The Sn–CT was dissolved in PGMEA with a concentration of 20 mg in 1 mL. Approximately 15 nm thin film was prepared for the sensitivity test (500 acceleration for 10 s, 7000 rpm for 45 s). The coated film was subjected to pre-exposure baking at 95 °C for 60 s. The exposed films were subjected to post-application baking at 110 °C for 90 s.

High-Resolution Pattern Development Using Electron Beam Irradiation. The thin films of Sn–CT on a silicon wafer were subjected to an electron beam for sensitivity studies and pattern development. The exposure energy and beam current used in the sensitivity investigation were 10, 20, and 28 keV at a 10 μ m aperture. Sn–CT thin films were then subjected to varying doses of e-beam (Raith, e-Line PLUS) radiation ranging from 0.01–3 mC/cm², followed by 90 s postexposure baking at 110 °C. The exposed thin films were then developed with MIBK: IPA (3:1) developer solution for 60 s followed by IPA rinsing for 10 s. LER/LWR values have been measured by using the SuMMIT software package (EUV Technology Corp.). High-Resolution Pattern Development Using Helium Ion Beam Irradiation. Thin films of Sn–CT were exposed to various doses of helium ion-beam radiation (Zeiss ORION NanoFab) of energy 25 keV, aperture 20 μ m, and beam current ~0.255 pA to demonstrate the potential of high-resolution nanopatterning of the proposed resist. Next, post-exposure baking at 110 °C for 90 s was carried out followed by developing in MIBK: IPA solution for 60 s and IPA washing.

Plasma Etching. Silicon etching was performed with a Reactive Ion Etching (RIE) System (PlanarRIE-6S). The process conditions were hard bake (130 °C for 5 min), 22 sccm SF₆ gas flow, and 40 W RF power at 15 mT chamber pressure. The resist thickness was measured using the AFM technique before and after the etching procedure. Stripping of the residual resist was done with oxygen– argon (50:50) plasma and the AFM technique was used to measure the height of the silicon features.

Electrical Characterizations. Electrical characterizations were performed using a high-precision Keithley 4200 semiconductor characterization system (SCS), with four source measuring units, cascaded with four probe stations in the frequency (f) range 10 kHz–1 MHz. The κ -value was measured on fabricating the MOS stacks using the formula $\kappa = C_{\text{ox}} \times t/(\varepsilon_0 \times A)$, where ε_0 denotes vacuum permittivity and A denotes the area of top Al circular electrodes, evaporated through a thermal evaporator at 1×10^{-6} mbar. t denotes the average thickness of the Sn–CT layer extracted from AFM profiling. Variable temperature I-V measurements were performed by using the LINKAM LTS420E heating stage.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsanm.2c04831.

Synthesis details of the cyclotrimeric organotin cage (Sn-CT); NMR data; IR data; TGA data; and SEM and AFM data (PDF)

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Notes

The authors declare no competing financial interest.

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REFERENCES

(1) Liang, B.; Wang, A.; Zhou, J.; Ju, S.; Chen, J.; Watanabe, K.; Taniguchi, T.; Shi, Y.; Li, S. Clean BN-Encapsulated 2D FETs with Lithography-Compatible Contacts. *ACS Appl. Mater. Interfaces* **2022**, *14*, 18697–18703.

(2) Namgung, S.; Koester, S. J.; Oh, S.-H. Ultraflat Sub-10 Nanometer Gap Electrodes for Two-Dimensional Optoelectronic Devices. *ACS Nano* **2021**, *15*, 5276–5283.

(3) Saifullah, M. S. M.; Tiwale, N.; Ganesan, R. Review of Metal-Containing Resists in Electron Beam Lithography: Perspectives for Extreme Ultraviolet Patterning. *J. Micro/Nanopattern. Mater. Metrol.* **2022**, *21*, No. 041402.

(4) Li, L.; Liu, X.; Pal, S.; Wang, S.; Ober, C. K.; Giannelis, E. P. Extreme Ultraviolet Resist Materials for Sub-7 nm Patterning. *Chem. Soc. Rev.* **2017**, *46*, 4855–4866.

(5) Gangnaik, A. S.; Georgiev, Y. M.; Holmes, J. D. New Generation Electron Beam Resists: A Review. *Chem. Mater.* **2017**, *29*, 1898–1917.

(6) He, Q.; Zhang, H. Nanoscale Patterning Hots Up. Nat. Electron. 2019, 2, 13-14.

(7) Luo, C.; Xu, C.; Lv, L.; Li, H.; Huang, X.; Liu, W. Review of Recent Advances in Inorganic Photoresists. *RSC Adv.* **2020**, *10*, 8385–8395.

(8) Wang, Z.; Yao, X.; An, H.; Wang, Y.; Chen, J.; Wang, S. Recent Advances in Organic-Inorganic Hybrid Photoresists. *J. Microelectron. Manuf.* **2021**, *4*, 1–8.

(9) Mojarad, N.; Hojeij, M.; Wang, L.; Gobrecht, J.; Ekinci, Y. Single-Digit-Resolution Nanopatterning with Extreme Ultraviolet Light for the 2.5 nm Technology Node and Beyond. *Nanoscale* **2015**, *7*, 4031–4037.

(10) Yang, J. K. W.; Cord, B.; Duan, H.; Berggren, K. K.; Klingfus, J.; Nam, S.-W.; Kim, K.-B.; Rooks, M. J. Understanding of Hydrogen Silsesquioxane Electron Resist for Sub-5-nm-Half-Pitch Lithography. J. Vac. Sci. Technol. B Microelectron. Nanometer. Struct. Process. Meas. Phenom. 2009, 27, 2622.

(11) Kenane, N.; Keszler, D. A. High-Resolution Lithographic Patterning with Organotin Films: Role of CO_2 in Differential

Dissolution Rates. ACS Appl. Mater. Interfaces 2021, 13, 18974–18983.

(12) Saifullah, M. S. M.; Asbahi, M.; Binti-Kamran Kiyani, M.; Tripathy, S.; Ong, E. A. H.; Ibn Saifullah, A.; Tan, H. R.; Dutta, T.; Ganesan, R.; Valiyaveettil, S.; Chong, K. S. L. Direct Patterning of Zinc Sulfide on a Sub-10 Nanometer Scale via Electron Beam Lithography. ACS Nano **201**7, *11*, 9920–9929.

(13) Yang, D.; Chen, X.; He, D.; Frommhold, A.; Shi, X.; Boden, S. A.; Lebedeva, M. A.; Ershova, O. V.; Palmer, R. E.; Li, Z.; Shi, H.; Gao, J.; Pan, M.; Khlobystov, A. N.; Chamberlain, T. W.; Robinson, A. P. G. A Fullerene – Platinum Complex for Direct Functional Patterning of Single Metal Atom-Embedded Carbon Nanostructures. *J. Phys. Chem. Lett.* **2022**, *13*, 1578–1586.

(14) Kim, J. W.; Bolten, J.; Moormann, C.; Kurz, H. Realization of Ultra-Thin HSQ Resist Layer for High Resolution Electron Beam Lithography Using Liquid Splitting Process. *Microelectron. Eng.* **2014**, *123*, 62–64.

(15) Lewis, S. M.; Hunt, M. S.; Derose, G. A.; Alty, H. R.; Li, J.; Wertheim, A.; De Rose, L.; Timco, G. A.; Scherer, A.; Yeates, S. G.; Winpenny, R. E. P. Plasma-Etched Pattern Transfer of Sub-10 nm Structures Using a Metal-Organic Resist and Helium Ion Beam Lithography. *Nano Lett.* **2019**, *19*, 6043–6048.

(16) Kumar, R.; Chauhan, M.; Moinuddin, M. G.; Sharma, S. K.; Gonsalves, K. E. Development of Nickel-Based Negative Tone Metal Oxide Cluster Resists for Sub-10 nm Electron Beam and Helium Ion Beam Lithography. *ACS Appl. Mater. Interfaces* **2020**, *12*, 19616– 19624.

(17) Cattoni, A.; Mailly, D.; Dalstein, O.; Faustini, M.; Seniutinas, G.; Rösner, B.; David, C. Sub-10 nm Electron and Helium Ion Beam Lithography Using a Recently Developed Alumina Resist. *Microelectron. Eng.* **2018**, *193*, 18–22.

(18) Saifullah, M. S. M.; Subramanian, K. R. V.; Kang, D. J.; Anderson, D.; Huck, W. T. S.; Jones, G. A. C.; Welland, M. E. Sub-10 nm High-Aspect-Ratio Patterning of ZnO Using an Electron Beam. *Adv. Mater.* **2005**, *17*, 1757–1761.

(19) Nandi, S.; Khillare, L.; Moinuddin, M. G.; Kumar, S.; Chauhan, M.; Sharma, S. K.; Ghosh, S.; Gonsalves, K. E. Macrocycle Network-Aided Nanopatterning of Inorganic Resists on Silicon. *ACS Appl. Nano Mater.* **2022**, *5*, 10268–10279.

(20) Saifullah, M. S. M.; Asbahi, M.; Neo, D. C. J.; Mahfoud, Z.; Tan, H. R.; Ha, S. T.; Dwivedi, N.; Dutta, T.; Bin Dolmanan, S.; Aabdin, Z.; Bosman, M.; Ganesan, R.; Tripathy, S.; Hasko, D. G.; Valiyaveettil, S. Patterning at the Resolution Limit of Commercial Electron Beam Lithography. *Nano Lett.* **2022**, *22*, 7432–7440.

(21) Thrun, X.; Choi, K.; Freitag, M.; Grenville, A.; Gutsch, M.; Hohle, C.; Stowers, J. K.; Bartha, J. W. Evaluation of Direct Patternable Inorganic Spin-on Hard Mask Materials Using Electron Beam Lithography. *Microelectron. Eng.* **2012**, *98*, 226–229.

(22) Del Re, R.; Passarelli, J.; Sortland, M.; Cardineau, B.; Ekinci, Y.; Buitrago, E.; Neisser, M.; Freedman, D. A.; Brainard, R. L. Low-Line Edge Roughness Extreme Ultraviolet Photoresists of Organotin Carboxylates. J. Micro/Nanolithogr., MEMS, MOEMS 2015, 14, No. 043506.

(23) Sharps, M. C.; Frederick, R. T.; Javitz, M. L.; Herman, G. S.; Johnson, D. W.; Hutchison, J. E. Organotin Carboxylate Reagents for Nanopatterning: Chemical Transformations during Direct-Write Electron Beam Processes. *Chem. Mater.* **2019**, *31*, 4840–4850.

(24) Bespalov, I.; Zhang, Y.; Haitjema, J.; Tromp, R. M.; Van Der Molen, S. J.; Brouwer, A. M.; Jobst, J.; Castellanos, S. Key Role of Very Low Energy Electrons in Tin-Based Molecular Resists for Extreme Ultraviolet Nanolithography. *ACS Appl. Mater. Interfaces* **2020**, *12*, 9881–9889.

(25) Ma, J. H.; Needham, C.; Wang, H.; Neureuther, A.; Prendergast, D.; Naulleau, P. Mechanistic Advantages of Organotin Molecular EUV Photoresists. *ACS Appl. Mater. Interfaces* **2022**, *14*, 5514–5524.

(26) Wang, D.; Yi, X.; Zhang, L. Non-Alkyl Tin-Oxo Clusters as New-Type Patterning Materials for Nanolithography. *Sci. China Chem.* **2022**, *65*, 114–119. (27) Grenville, A.; Anderson, J. T.; Clark, B. L.; De Schepper, P.; Edson, J.; Greer, M.; Jiang, K.; Kocsis, M.; Meyers, S. T.; Stowers, J. K. Integrated Fab Process for Metal Oxide EUV Photoresist. *Proc. SPIE* **2015**, 94250, 94250S.

(28) Yildirim, O.; Buitrago, E.; Hoefnagels, R.; Meeuwissen, M.; Wuister, S.; Rispens, G.; van Oosten, A.; Derks, P.; Finders, J.; Vockenhuber, M.; Ekinci, Y. Improvements in Resist Performance towards EUV HVM. *Proceedings SPIE 10143, Extreme Ultraviolet* (EUV) Lithography VIII, 2017; 101430Q.

(29) Yin, H. D.; Hong, M.; Yang, M. L.; Cui, J. C. Cyclotrimeric and Weakly-Bridged Cyclotetrameric Organotin(IV) Compounds Assembled from 5-Hydroxyisophthalic Acid: Synthesis and Structural Characterization. J. Mol. Struct. **2010**, *984*, 383–388.

(30) Chaker, A.; Alty, H. R.; Tian, P.; Kotsovinos, A.; Timco, G. A.; Muryn, C. A.; Lewis, S. M.; Winpenny, R. E. P. Nanoscale Patterning of Zinc Oxide from Zinc Acetate Using Electron Beam Lithography for the Preparation of Hard Lithographic Masks. *ACS Appl. Nano Mater.* **2021**, *4*, 406–413.

(31) Lewis, S. M.; Fernandez, A.; DeRose, G. A.; Hunt, M. S.; Whitehead, G. F.; Lagzda, A.; Alty, H. R.; Ferrando-Soria, J.; Varey, S.; Kostopoulos, A. K.; Schedin, F.; Winpenny, R. E. P. Use of Supramolecular Assemblies as Lithographic Resists. *Angew. Chem., Int. Ed.* **2017**, *129*, 6853.

(32) Shi, J.; Ravi, A.; Richey, N. E.; Gong, H.; Bent, S. F. Molecular Layer Deposition of a Hafnium-Based Hybrid Thin Film as an Electron Beam Resist. *ACS Appl. Mater. Interfaces* **2022**, *14*, 27140–27148.

(33) Thakur, N.; Reddy, P. G.; Nandi, S.; Yogesh, M.; Sharma, S. K.; Pradeep, C. P.; Ghosh, S.; Gonsalves, K. E. New Non-Chemically Amplified Molecular Resist Design with Switchable Sensitivity for Multi-Lithography Applications and Nanopatterning. *J. Micromech. Microeng.* **2017**, *27*, No. 125010.

(34) Xu, H.; Sakai, K.; Kasahara, K.; Kosma, V.; Yang, K.; Herbol, H. C.; Odent, J.; Clancy, P.; Giannelis, E. P.; Ober, C. K. Metal-Organic Framework-Inspired Metal-Containing Clusters for High-Resolution Patterning. *Chem. Mater.* **2018**, *30*, 4124–4133.

(35) Shi, X.; Prewett, P.; Huq, E.; Bagnall, D. M.; Robinson, A. P. G.; Boden, S. A. Helium Ion Beam Lithography on Fullerene Molecular Resists for Sub-10 nm Patterning. *Microelectron. Eng.* **2016**, *155*, 74–78.

(36) Ravi Kiran, N.; Chauhan, M.; Sharma, S. K.; Ghosh, S.; Gonsalves, K. E. Resists for Helium Ion Beam Lithography: Recent Advances. *ACS Appl. Electron. Mater.* **2020**, *2*, 3805–3817.

(37) Reddy, P. G.; Thakur, N.; Lee, C.; Chien, S.; Pradeep, C. P.; Ghosh, S.; Tsai, K.; Gonsalves, K. E. Heavy Metal Incorporated Helium Ion Active Hybrid Non-Chemically Amplified Resists: Nano-Patterning with Low Line Edge Roughness. *AIP Adv.* **2017**, *7*, No. 085314.

(38) Winston, D.; Cord, B. M.; Ming, B.; Bell, D.; Dinatale, W.; Stern, L.; Vladar, A.; Postek, M.; Mondol, M.; Yang, J.; Berggren, K. K. Scanning-helium-ion-beam lithography with hydrogen silsesquioxane resist. J. Vac. Sci. Technol., B **2009**, *27*, 2702–2706.

(39) Lu, X. Y.; Luo, H.; Wang, K.; Zhang, Y. Y.; Zhu, X. F.; Li, D.; Ma, B.; Xiong, S.; Nealey, P. F.; Li, Q.; Wu, G. P. CO2-Based Dual-Tone Resists for Electron Beam Lithography. *Adv. Funct. Mater.* **2021**, *31*, No. 2007417.

(40) Manfrinato, V. R.; Zhang, L.; Su, D.; Duan, H.; Hobbs, R. G.; Stach, E. A.; Berggren, K. K. Resolution Limits of Electron-Beam Lithography toward the Atomic Scale. *Nano Lett.* **2013**, *13*, 1555–1558.

(41) Yi, X.; Wang, D.; Li, F.; Zhang, J.; Zhang, L. Molecular Bixbyite-like In12-Oxo Clusters with Tunable Functionalization Sites for Lithography Patterning Applications. *Chem. Sci.* **2021**, *12*, 14414–14419.

(42) Hu, S.; Chen, J.; Yu, T.; Zeng, Y.; Wang, S.; Guo, X.; Yang, G.; Li, Y. A Novel Dual-Tone Molecular Glass Resist Based on Adamantane Derivatives for Electron Beam Lithography. *J. Mater. Chem. C* 2022, *10*, 9858–9866. (43) Nandi, S.; Yogesh, M.; Reddy, P. G.; Sharma, S. K.; Pradeep, C. P.; Ghosh, S.; Gonsalves, K. E. A Photoacid Generator Integrated Terpolymer for Electron Beam Lithography Applications: Sensitive Resist with Pattern Transfer Potential. *Mater. Chem. Front.* **2017**, *1*, 1895–1899.

www.acsanm.org

(44) Tiwale, N.; Subramanian, A.; Kisslinger, K.; Lu, M.; Kim, J.; Stein, A.; Nam, C. Y. Advancing next Generation Nanolithography with Infiltration Synthesis of Hybrid Nanocomposite Resists. *J. Mater. Chem. C* 2019, *7*, 8803–8812.

(45) Lewis, S. M.; Derose, G. A.; Alty, H. R.; Hunt, M. S.; Lee, N.; Mann, J. A.; Grindell, R.; Wertheim, A.; Rose, L.; Fernandez, A.; Muryn, C. A.; Whitehead, G. F. S.; Timco, G. A.; Scherer, A.; Winpenny, R. E. P. Tuning the Performance of Negative Tone Electron Beam Resists for the Next Generation Lithography. *Adv. Funct. Mater.* **2022**, *32*, No. 2202710.

(46) Passarelli, J.; Murphy, M.; Del Re, R.; Sortland, M.; Hotalen, J.; Dousharm, L.; Fallica, R.; Ekinci, Y.; Neisser, M.; Freedman, D. A.; Brainard, R. L. Organometallic Carboxylate Resists for Extreme Ultraviolet with High Sensitivity. *J. Micro/Nanolithogr. MEMS MOEMS* **2015**, *14*, No. 043503.

(47) Li, L.; Chakrabarty, S.; Spyrou, K.; Ober, C. K.; Giannelis, E. P. Studying the Mechanism of Hybrid Nanoparticle Photoresists: Effect of Particle Size on Photopatterning. *Chem. Mater.* **2015**, *27*, 5027–5031.

(48) Kataoka, S.; Sue, K. Enhanced Solubility of Zirconium Oxo Clusters from Diacetoxyzirconium(IV) Oxide Aqueous Solution as Inorganic Extreme-Ultraviolet Photoresists. *Eur. J. Inorg. Chem.* **2022**, *12*, No. e202200050.

(49) Austin, M. D.; Zhang, W.; Ge, H.; Wasserman, D.; Lyon, S. A.; Chou, S. Y. 6 nm Half-Pitch Lines and 0.04 μ m² Static Random Access Memory Patterns By Nanoimprint Lithography. *Nanotechnology* **2005**, *16*, 1058–1061.

(50) Krishtab, M.; Stassen, I.; Stassin, T.; Cruz, A. J.; Okudur, O. O.; Armini, S.; Wilson, C.; De Gendt, S.; Ameloot, R. Vapor-Deposited Zeolitic Imidazolate Frameworks as Gap-Filling Ultra-Low-κ Dielectrics. *Nat. Commun.* **2019**, *10*, 3729.

(51) da Silva, R. M. L.; Albano, L. G. S.; Vello, T. P.; de Araújo, W. W. R.; de Camargo, D. H. S.; Palermo, L. D.; Corrêa, C. C.; Wöll, C.; Bufon, C. C. B. Surface-Supported Metal-Organic Framework as Low-Dielectric-Constant Thin Films for Novel Hybrid Electronics. *Adv. Electron. Mater.* **2022**, *8*, No. 2200175.

(52) Xie, M.; Li, M.; Sun, Q.; Fan, W.; Xia, S.; Fu, W. Research Progress on Porous Low Dielectric Constant Materials. *Mater. Sci. Semicond. Process.* **2022**, *139*, No. 106320.

(53) Baklanov, M. R.; de Marneffe, J.-F.; Shamiryan, D.; Urbanowicz, A. M.; Shi, H.; Rakhimova, T. V.; Huang, H.; Ho, P. S. Plasma Processing of Low- κ Dielectrics. J. Appl. Phys. **2013**, 113, No. 041101.

(54) Wilson, D. W.; Muller, R. E.; Echternach, P. M.; Backlund, J. P. Electron-Beam Lithography for Micro- and Nano-Optical Applications. *Micromach. Technol. Micro-Optics Nano-Optics III* **2005**, 5720, 68.

(55) Palankar, R.; Medvedev, N.; Rong, A.; Delcea, M. Fabrication of Quantum Dot Microarrays Using Electron Beam Lithography for Applications in Analyte Sensing and Cellular Dynamics. *ACS Nano* **2013**, *7*, 4617–4628.

(56) Terris, B. D.; Thomson, T. Nanofabricated and Self-Assembled Magnetic Structures as Data Storage Media. *J. Phys. D: Appl. Phys.* **2005**, *38*, R199.

(57) Frederick, R. T.; Saha, S.; Diulus, J. T.; Luo, F.; Amador, J. M.; Li, M.; Park, D.; Garfunkel, E. L.; Keszler, D. A.; Herman, G. S. Thermal and Radiation Chemistry of Butyltin Oxo Hydroxo: A Model Inorganic Photoresist. *Microelectron. Eng.* **2019**, *205*, 26–31.

(58) Frederick, R. T.; Diulus, J. T.; Hutchison, D. C.; Nyman, M.; Herman, G. S. Effect of Oxygen on Thermal and Radiation-Induced Chemistries in a Model Organotin Photoresist. *ACS Appl. Mater. Interfaces* **2019**, *11*, 4514–4522.

(59) Zhang, Y.; Haitjema, J.; Liu, X.; Johansson, F.; Lindblad, A.; Castellanos, S.; Ottosson, N.; Brouwer, A. M. Photochemical Conversion of Tin-oxo Cage Compounds Studied Using Hard Xray Photoelectron Spectroscopy. J. Micro/Nanolithogr., MEMS, MOEMS 2017, 16, No. 023510.

(60) Qiao, H.; Zheng, Z.; Zhang, L.; Xiao, L. SnO2@C Core-Shell Spheres: Synthesis, Characterization, and Performance in Reversible Li-Ion Storage. *J. Mater. Sci.* **2008**, *43*, 2778–2784.

(61) Diulus, J. T.; Frederick, R. T.; Hutchison, D. C.; Lyubinetsky, I.; Addou, R.; Nyman, M.; Herman, G. S. Effect of Ambient Conditions on Radiation-Induced Chemistries of a Nanocluster Organotin Photoresist for Next-Generation EUV Nanolithography. *ACS Appl. Nano Mater.* **2020**, *3*, 2266–2277.

(62) Capitan, M. J.; Alvarez, J.; Navio, C. Study of the Electronic Structure of Electron Accepting Cyano-Films: TCNQ versus TCNE. *Phys. Chem. Chem. Phys.* **2018**, *20*, 10450–10459.

(63) Choudhary, S.; Schwarz, D.; Funk, H. S.; Khosla, R.; Sharma, S. K.; Schulze, J. Impact of Charge Trapping on Epitaxial P-Ge-on-p-Si and HfO₂Based Al/HfO₂/p-Ge-on-p-Si/Al Structures Using Kelvin Probe Force Microscopy and Constant Voltage Stress. *IEEE Trans. Nanotechnol.* **2021**, *20*, 346–355.

(64) Khosla, R.; Sharma, S. K. Frequency Dispersion and Dielectric Relaxation in Postdeposition Annealed High-κ Erbium Oxide Metal– Oxide–Semiconductor Capacitors. J. Vac. Sci. Technol., B 2018, 36, No. 012201.

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