Tuning the Performance of Negative Tone Electron Beam Resists for the Next Generation Lithography

Scott M. Lewis,* Guy A. DeRose, Hayden R. Alty, Matthew S. Hunt, Nathan Lee, James A. Mann, Richard Grindell, Alex Wertheim, Lucia De Rose, Antonio Fernandez, Christopher A. Muryn, George F. S. Whitehead, Grigore A. Timco, Axel Scherer, and Richard E. P. Winpenny

A new class of electron beam negative tone resist materials has been developed based on heterometallic rings. The initial resist performance demonstrates a resolution of 15 nm half-pitch but at the expense of a low sensitivity. To improve sensitivity a 3D Monte Carlo simulation is used that utilizes a secondary and Auger electron generation model. The simulation suggests that the sensitivity can be dramatically improved while maintaining high resolution by incorporating appropriate chemical functionality around the metal–organic core. The new resists designs based on the simulation have the increased sensitivity expected and illustrate the value of the simulation approach.

1. Introduction

Electron beam lithography (EBL) enables modern electronic devices such as fin field-effect transistors (FinFETs) to be fabricated to dimensions down to 9 nm pitch.[1] EBL is mainly found in research laboratories as it has been excluded from mass manufacturing of integrated circuits because it is a sequential process and hence inherently slow. New EBL tools that are designed for photomask production are in development. These tools have 262,144 beams and they have demonstrated a half-pitch resolution capability of 11 nm.[2] However, the exposure times required to expose a wafer are still considerable.

One of the defining parameters is the exposure interaction efficiency of the resist material. The exposure efficiency is defined by the number of the incident electrons required to fabricate a nano feature and it is inversely proportional to the energy of the incident electrons that is essential to produce a feature. This is limited by the energy dissipation of the electrons that have traveled into the resist material which is known as the stopping power. Therefore, to increase exposure efficiency while maintaining maximum resolution the stopping power must be increased. This may be achieved by decreasing the energy of the electrons, but this increases the overall spot size of the beam and will inherently increase the proximity effect and lower resolution. This is where the exposure dose contributes to widening the developed pattern in comparison to the desired scanned pattern.

The exposure efficiency could also be addressed by understanding the electron beam behavior in the resist material, and by modifying the resist to obtain the performance required to produce the next-generation devices. Existing resists such as polymethylmethacrylate (PMMA), ZEP520A[3] (a methylstrene and chloromethylacylate co-polymer), and inorganic resists such as hydrogen silsesquioxane (HSQ)[4] can offer very high resolution, but do not offer the exposure efficiency required. Chemically amplified resists (CARs) such as 40XT/PEDOT-PSS (an acidic poly(3,4-ethylenedioxythiophene)poly(styrene-sulfonate) composite),[5] P(HEMA-co-MAAEMA) (a poly(2-hydroxethyl methacrylate-co-2-methacrylamido-ethyl methacrylate) block copolymer)[6] and the fullerene family resists called IM-MFP12-8[7,8] offer very high sensitivity but at the expense of resolution. Therefore, to use EBL to follow the semiconductor technology roadmap,[9] new resist materials are needed that exhibit properties for mass manufacture at the nanoscale that allows the further advancement of electronic devices.

We have reported in a previous study a negative tone resist that is based on a metal–organic compound.[10] The performance of this resist achieved 20 nm half-pitch lines while exhibiting an extraordinary silicon dry etch performance of >50:1 selectivity. Unfortunately, to achieve this, the resist was demonstrated with very high exposure dose of 61 000 μC cm−2. To expand on this work, we have used a 3D Monte Carlo simulator[11,12] to understand the exposure mechanism to improve the exposure efficiency of the resist. This has led us to significantly improve the...
resist chemistry to achieve high-resolution patterns while exhibiting low exposure doses. These results are presented here.

2. Results and Discussion

Preliminary Monte Carlo modeling led us to study a resist that is based on a metal–organic compound \( \text{[Cr}_7\text{NiF}_8\text{(O}_2\text{CtBu})_{16}] \) where seven chromium(III) centers (in green in Figure 1) form an octagon.\(^{11}\) The exterior of the compound entirely of tert-butyl groups, and this gives the compound high solubility in solvents suitable for preparing films on silicon substrates. The compound has a density \( (\rho = 1.212 \text{ g cm}^{-3}) \) with a large molecular weight (2192 Daltons). The beauty of this compound is that when spun on a surface, it forms a close-packed film.\(^{14}\) As we will show, this is a high resolution but low sensitivity resist.

To improve the sensitivity, a secondary electron (SE)-generating agent was incorporated into the molecule. This is achieved by changing the central ammonium cation from di-n-propylammonium to diallylammonium to give \( \text{[NH}_2\text{(CH}_2\text{=CH=CH}_2\text{)}_2\text{NH}_3]\) with a large molecular weight (2192 Daltons). The beauty of this compound is that when spun on a surface, it forms a close-packed film.\(^{14}\) As we will show, this is a high resolution but low sensitivity resist.

For exposing the resist and subsequently increase the overall sensitivity while contributing to the proximity effect.

The simulations show that incorporating both the diallylammonium (in 2 and 3) and heavy metal (in 3) leads to further SEs being ejected, lowering the exposure dose. The increase in sensitivity to replacing di-n-propylammonium with diallylammonium is due to a two-step process where the diallylammonium alkene groups when struck by the incident electron generate SEs. These SEs are in close proximity to Cr atoms in the resist; Cr has a larger electron energy stopping power than that of the C, N, and H atoms in the organic molecule and therefore the Cr atoms are then activated to generate further SEs. These electrons are produced at a reduced electron energy and have a greater probability of interaction with the C, N, and H atoms in the outer region of the resist because the probability of causing a collision is high. Hence, cleaving the organics on the outside of the molecule, rendering the resist insoluble in the developing solvent. Thus, this has the effect of reducing the exposure dose while maintaining resolution. The presence of the Cr atoms around the diallylammonium has an amplifying effect on the increase in sensitivity.

The addition of \( \text{HgCl}_2 \) markedly increases the density of the resist and therefore, the PEs will experience more collisions as the effective mean free path is greatly reduced. The higher atomic number of Hg also increases the possibility to generate SEs by ejecting electrons from the outer orbitals, and therefore the probability of an inelastic scattering event is much higher in 3. In addition, at 100 KeV the energy of the incident beam is above the activation energy required to emit AEs from the Hg 1S orbital (83.1 KeV). The probability of striking these 1S electrons is low but the AEs have an increased probability of striking the electrons in the higher orbitals. Hence, this will have an effect of producing a more sensitive resist. These AEs and SEs will experience an increased number of scattering events (due to that their associated energy is considerably lower than that of the PE) and these collisions generate even more SEs. This is significant, as it can be seen from Figure 2e,f that the SE, are scattered at angles larger than 80˚ in arbitrary trajectories away from the primary beam. These electrons expose the resist laterally producing the nanostructure.

Figure 3 shows the number of SEs and AEs generated inside each of the resists. At energies between 10 and 50 KeV, the PEs are slow enough to cause multiple inelastic scattering events and generate many SEs. Therefore, the sensitivity of resist is

![Figure 1. The structures of compounds in the crystal: a) 1; b) 2; c) 3. Cr green, Ni green with a blue band, F yellow, C gray, H atoms omitted for clarity.](image-url)
increased at lower energies but usually at the cost of poorer resolution. At higher energies (50 to 100 KeV) the probability to generate a SE is reduced, and more PEs are required to increase the probability of causing a collision event, meaning the exposure efficiency is low. The introduction of HgCl$_2$ in 3 markedly increases the number of SEs generated when compared to 1.
As the film thickness is 15 nm, at the larger energies of 50 to 100 KeV, there are not enough atoms in the film for all the PEs to lose energy and generate SEs. The consequence is that a substantial number of PEs will reach deep into the silicon substrate below or they will be backscattered into the underside of the resist material, approximately 30–40 µm away from the immediate exposure area. Thus, higher resolution can be achieved by exposing the resist with 100 KeV tool by confining the forward scattering electrons to the incident beam inside the resist, but at the expense of longer writing times.

To build on the result and the explanation of Figure 3a, the number of AEs generated gives a significant contribution to the overall sensitivity of the resist and this is shown in Figure 3b. In all resist cases, the metal core is Cr, therefore the probability of emitting low energy AEs from the 1S shell can be achieved because the associated energy of ionizing with an electron in this shell is 5989 eV and the minimum incident electron energy shown in Figure 3b is 10 KeV. Clearly, incident electrons with energies larger than the Cr electron ground state can benefit from this process, however, the probability of emitting AEs when using incident electrons with significantly higher energies (50 KeV and above) will be lower as the scattering interaction is decreased (Figure 3b). Resist 3 contains HgCl₂ and consequently does not have the same issues as resists 1 and 2 because the Hg component requires an incident electron with an energy greater than 83.1 KeV to ionize with an electron in the 1S shell. Moreover, Hg has a larger number of shells that could emit an AE than the atoms present in resists 1 and 2. This can be advantageous because as the incident electron travels through the resist, it loses more and more energy upon each collision. As a result, the electrons in these higher orbitals would be ionized by these incident electrons to emit low energy AEs (providing that the excitation energy of the secondary AEs is correct). This is important because these low energy AE now become the incident electrons and are free to collide with the atoms within the molecule and upon each collision, increases the statistical chance of generating further SEs and secondary Auger electrons (their energy will be reduced more than the first generation). Hence causing an avalanche effect of cascading electrons in the immediate exposure area, leading to a significant reduction in exposure dose and this is demonstrated by Figure 3b.

Figure 4a shows the total number of SEs and AEs that are generated in the three resist materials as the incident electrons are accelerated at 30 and 100 KeV respectively; this was generated from Figure 3. Figure 4b shows the number of SEs and AEs generated in all resist films compared to the number of SEs generated in 1.

The immediate observation is that the addition of the diallylammmonium and HgCl₂ in resist 3 increases the total number of electrons that are emitted by 2.6 or 3.36 times, compared with 1 at the acceleration voltages of 30 and 100 KeV respectively; this was generated from Figure 3. Figure 4b shows the number of SEs and AEs generated in all resist films compared to the number of SEs generated in 1.

The maximum write speed that can be theoretically achieved by using resist 3 will increase by the same factor.

Figure 3. The number of electrons generated in a 15 nm thick films of resists 1, 2, and 3 on 50 nm thick Silicon. a) Total number of SEs generated (100 KeV data points are resists 1, 2, and 3 are 261, 500, and 681 respectively), b) Total number of Auger electrons generated from the resist materials (100 KeV data points are resists 1, 2, and 3 are 64, 136, and 189 respectively). Resist 1, dotted line; 2, dashed line; 3, full line.

Figure 4. a) A comparison between the number of secondary and Auger electrons generated at 30 and 100 KeV for the three resist materials, b) The ratio of secondary and Auger electrons generated compared to 1 at 30 and 100 KeV.
For both energies considered, the molecular properties of the resist confine the forward scattering electrons to within the incident beam inside the resist, hence high resolution features are found. Figure 5a,d,g,j,m,q shows a profile view of a 3D Monte Carlo simulation that models an exposure pattern which consists of 20 lines for each resist at acceleration voltages of 30 and 100 KeV. Each model shows nanostructures with line widths of 15 nm half-pitch that are 1 µm long. The step size of the electron beam was 4 and 5 nm at acceleration voltages of 30 and 100 KeV respectively. The scattering trajectory plot of each resist is directly compared with the nanostructures that were fabricated in each resist.

The nanostructures shown in Figure 5b,e,h,k,n,r were created by dicing silicon wafers into 20 mm × 20 mm pieces. Each resist (30 mg) was dissolved in tert butyl methyl ether (3 g). Each solution was filtered using a 0.2 µm polytetrafluoroethylene syringe filter and was spun onto substrates with a spin rate of 6000 rpm for 30 s, followed by a 100 °C soft bake for 2 min to evaporate the solvent. The lithography was performed using a Raith EPBG5200 for high acceleration voltage exposures and for low voltage exposures was performed using an FEI Sirion scanning electron microscope (SEM) where the electron beam was controlled using Raith ELPHY quantum pattern generator. The exposure clearing dose of each resist was determined using a one-dimensional matrix of single-pixel-wide lines that had a pitch of 30 nm and were 5 µm long. The current and step sizes used were 50 pA, 4 nm, and 100 pA, 5 nm for the 30 KeV and 100 KeV exposures respectively. The patterns were exposed using an acceleration voltage of 30 KeV were exposed in sets of 20 lines with one pass of the beam per line, and the line dose of each set ranged from 1000 to 20 950 µC cm⁻² with incremental steps of 50 µC cm⁻², whereas for the acceleration voltage of 100 KeV, the patterns were exposed in sets of 20 lines with one pass of the beam per line, and the line dose of each set ranged from 1000 to 50 950 µC cm⁻² with incremental steps of 50 µC cm⁻². Following lithography, the resist was developed in hexane for 10 s to dissolve away the unexposed resist, then blown dry with nitrogen.

The SEM images seen in Figure 5 show 15 nm half-pitch lines in blocks of 20 lines that have been patterned in all three resists using 30 and 100 KeV accelerating voltages. Comparing each resist, it can be seen that each resist has achieved a resolution of 15 nm half-pitch with good uniformity. While each resist achieved the same resolution it was determined that the sensitivity of each is dramatically different. It can be seen that resist 1 (Figure 5a) is the least sensitive to the electron beam of the 3 resists. Figure 5a shows that the dose factor (DF) was measured to be 12 and by multiplying this by the base dose (1000 µC cm⁻²) equated the dose to be 12 000 µC cm⁻². However, the insets of Figure 5a show that the pattern that was produced with a dose factor of 11 (giving a dose of 11 000 µC cm⁻²) had completely collapsed as is it under exposed and that first 4 lines in the pattern have collapsed as well, therefore the actual exposure dose to resolve the 15 nm half-pitch pattern was 12 200 µC cm⁻².

To produce the same pattern of lines with 15 nm half-pitch, resists 2 and 3 (Figure 5b,c), gave sensitivities of 7500 and 4700 µC cm⁻² respectively, this is to be expected from the Monte Carlo simulations. Interestingly, at the higher doses of 24 000 µC cm⁻² it can be seen that the pattern produced with resist 1 is not overexposed, however, the pattern resolved using the same dose of 24 000 µC cm⁻² in resist 3 that pattern is overexposed (see Inset of Figure 5c).

At the acceleration voltage of 100 KeV, it can be seen that resist 1 (Figure 5d) behaved as it did when it was exposed with a low acceleration voltage of 30 KeV as it was found to be the least sensitive to the electron beam. The dose was measured to be 40 000 µC cm⁻² whereas resists 2 and 3 (Figure 5e,f) yielded sensitivities of 20 600 and 12 000 µC cm⁻² respectively. Like the low acceleration voltage experiments, it was determined that the sensitivity of resist 3 was increased when compared to resist 1, which again matches the behavior seen in the Monte Carlo simulations. It must be noted that the overexposed image in the inset image of Figure 5f shows that it takes more electrons to overexpose the resist (DF = 48 equating to a dose of 48 000 µC cm⁻²), resist 3 has 4.1 times more exposure than resist 1 and still produces patterns with 15 nm half-pitch with good line uniformity.

Building upon the results shown in Figure 5, Figure 6 shows SEM tilted images of 15 nm half-pitch lines in all three resists which have been patterned using 30 and 100 KeV accelerating voltages. At first glance, it appears that all of the simulations and the nanostructures in the SEM images appear to be the same and that this is the point. What is different is the exposure dose that is required to fully render each resist insoluble in the developer, which is hexane. The exposure dose that is required to fully expose each resist is significantly reduced when functionalizing resist 1 with diallylammonium and HgCl₂ to give 3. It can be seen that the pattern resolution has not changed because the resist design rules (large density and large molecular weight to obtain high resolution nanostructures) that govern the pattern were met. SEs create nanostructures by damaging the resist molecule, rendering it insoluble in the developing solvent. Therefore, by super imposing the SEs that are generated in the Monte Carlo simulation (Figure 6a,d,g,j,m,q) on the SEM micrograph (Figure 6c,f,i,l,o,s), it appears that the first generation of SEs (red) play the most dominant role, but in fact, it is the 2nd generation electrons (unfortunately, the first generation SEs masks the concentration of 2nd generation SEs) that are responsible for the exposure and distance that these electron\'s travel is less than 10 nm. Table 1 lists the calculated number of SEs and AEIs involved in producing the 15 nm in each of the three resists and at 30 and 100 KeV.

Figure 7a shows the exposure doses required to produce the patterns shown in Figure 5. It is evident that the presence of diallylammonium in 2 and diallylammonium and HgCl₂ in 3 decreases the exposure dose. The results agree remarkably well with the Monte Carlo simulation (Figure 7b) demonstrating that we have chemical control of the exposure dose. Thus, the dose required for 3 is reduced by a factor of 2.58 and 3.33 times when compared to 1 at 30 and 100 KeV respectively.

Comparing the sensitivity of resist 3 to the [Cr₈F₆(O₂C₅H₅)₆]₁₆⁻ resist that was presented in a previous study, we have shown that by understanding the exposure mechanism we have increased the resist sensitivity by a factor of 10. There appears to be no further gains using 100 KeV electrons because the nanostructures produced using the 30 KeV electrons have the
Figure 5. a) Scanning electron micrographs of developed patterns of 15 nm half-pitch lines fabricated in 1 using 30 KeV acceleration voltage using a dose scale; b) Scanning electron micrographs of developed patterns of 15 nm half-pitch lines fabricated in 2 using 30 KeV acceleration voltage using a dose scale; c) Scanning electron micrographs of developed patterns of 15 nm half-pitch lines fabricated in 3 using 30 KeV acceleration voltage using a dose scale; d) Scanning electron micrographs of developed patterns of 15 nm half-pitch lines fabricated in 1 using 100 KeV acceleration voltage using a dose scale; e) Scanning electron micrographs of developed patterns of 15 nm half-pitch lines fabricated in 2 using 100 KeV acceleration voltage using a dose scale; f) Scanning electron micrographs of developed patterns of 15 nm half-pitch lines fabricated in 3 using 100 KeV acceleration voltage using a dose scale.
Figure 6. The internal electron scattering interactions inside 15 nm half-pitch lines simulated in: a) 1 using 30 KeV acceleration voltage with 30 500 incident electrons per spot; b) Scanning electron micrographs of developed patterns of 15 nm half-pitch lines fabricated in 1 using 30 KeV acceleration voltage using a dose of 12 200 µC cm$^{-2}$; c) Monte Carlo simulation of SEs that are superimposed on the developed pattern that is shown in (b); d) 2 using 30 KeV acceleration voltage with 18 750 incident electrons per spot; e) Scanning electron micrographs of developed patterns of 15 nm half-pitch lines fabricated in 2 using 30 KeV acceleration voltage using a dose of 7500 µC cm$^{-2}$; f) Monte Carlo simulation of SEs that are superimposed on the developed pattern that is shown in (e); g) 3 using 30 KeV acceleration voltage with 11 800 incident electrons per spot; h) Scanning electron micrographs of developed patterns of 15 nm half-pitch lines fabricated in 3 using 30 KeV acceleration voltage using a dose of 4700 µC cm$^{-2}$; i) Monte Carlo simulation of SEs that are superimposed on the developed pattern that is shown in (h); j) 1 using 100 KeV acceleration voltage with 124 950 incident electrons per spot; k) Scanning electron micrographs of developed patterns of 15 nm half-pitch lines fabricated in 1 using 100 KeV acceleration voltage using a dose of 40 000 µC cm$^{-2}$; l) Monte Carlo simulation of SEs that are superimposed on the developed pattern that is shown in (k); m) 2 using 100 KeV acceleration voltage with 64 200 incident electrons per spot; n) Scanning electron micrographs of developed patterns of 15 nm half-pitch lines fabricated in 2 using 100 KeV acceleration voltage using a dose of 20 600 µC cm$^{-2}$; o) Monte Carlo simulation of SEs that are superimposed on the developed pattern that is shown in (n); q) 3 using 100 KeV acceleration voltage with 37 500 incident electrons per spot; r) Scanning electron micrographs of developed patterns of 15 nm half-pitch lines fabricated in 3 using 100 KeV acceleration voltage using a dose of 12 000 µC cm$^{-2}$; s) Monte Carlo simulation of SEs that are superimposed on the developed pattern that is shown in (r).
same critical dimension. Using low energy electrons reduces the cost of the process because the initial cost of a low energy EBL tool is considerably less expensive than their high energy counterparts.

Figure 8 shows the X-ray photoelectron spectra (XPS) of resist 3 before and after electron beam exposure. This was resist chosen because it has all of the additives. The spectra have been normalized with respect to the Carbon 1S peak for clarity. Inset C 1S of Figure 8 shows the Carbon 1S peak. It can be seen that the main peak is the same before and after exposure, however, the side peak that represents the O—C=O part of molecule has been significantly reduced after exposure. This is because the electron beam decomposes the carboxylates leaving only the chromium atoms of the main ring-like structure. The consequence of this is that this process changes the molecule solubility where it is no longer soluble in hexane upon the development process.

Inset Cr 2p of Figure 8 shows that after exposure to the electron beam the chromium 2p peak has broadened and shows an apparent shift to the right. This can be explained that the chromium is changing from a single oxidation state to a mixture of states including more reduced states resulting in the broadening and apparent shift. This suggests that chromium is being reduced away towards a mixture of CrO$_x$F$_y$ compounds which are also not soluble in hexane. The oxygen is forming carbon dioxide (CO$_2$) or/and carbon monoxide (CO) products and these gases are diffusing out of the film into the vacuum. The mercury peaks are clearly visible before exposure and after exposure, they have vanished, this is due to that upon exposure the mercury ejects a SE becomes dissociated from the main molecule and then sublimes from the film this is because its vapor pressure is very low.

All resist materials exhibited extremely high dry etch selectivity when compared with silicon. Figure 9a–c show 15 nm half-pitch lines that have been patterned into resist 1, 2, and 3 respectively. In each case, an acceleration voltage of 100 KeV was used. The underlying silicon was then etched with a Pseudo Bosch process that uses inductively coupled plasma (ICP) of SF$_6$ and C$_4$F$_8$ gases (Figure 9d–f). The resolution of the silicon nanostructures post-etch was 9 nm, with a height of 14.6 nm (Figure 9d–f). The remaining resist thickness is measured to be 14.2 nm, which leads to the resist etch rate of 0.022 nm s$^{-1}$, while the silicon depth was 24 nm giving an etch rate of 1.33 nm s$^{-1}$. Thus, the etch selectivity of all these resists is 60:1 with respect to silicon.

This is approximately the equivalent selectivity that is achieved with aluminum oxide masks,$^{[15]}$ which were to this point the best masks available, and which require more processing steps compared with our process. The resist layers were removed by wet etching the silicon dioxide (SiO$_2$) layer immediately beneath the resist using buffered hydrofluoric acid for 30 s giving the resultant silicon nanostructures (Figure 8g–i).

Other high resolution resists such as PMMA, ZEP520A, and HSQ have etch selectivities of only 2:1, 2.9:1, and 4.2:1 respectively.$^{[16]}$ Considering the HSQ resist case, the resist materials

| Resist | Voltage [KeV] | Secondary electrons | Auger electrons |
|--------|---------------|---------------------|-----------------|
|        |               | 1st  | 2nd  | 3rd  | 4th  |
| 1      | 30            | 19170 | 31456 | 3654  | 1162  | 31072 |
| 1      | 100           | 5058  | 20990 | 892   | 284   | 18744 |
| 2      | 30            | 21066 | 39066 | 4172  | 1296  | 30742 |
| 2      | 100           | 9972  | 45216 | 1894  | 644   | 36236 |
| 3      | 30            | 22400 | 41638 | 4526  | 1406  | 39966 |
| 3      | 100           | 10254 | 11176 | 2056  | 568   | 39766 |

Table 1. Calculated SEs and AEs to produce 15 nm resolution patterns in 1, 2, and 3 at 30 and 100 KeV.

Figure 7. a) Electron exposure clearing doses for all resist material. b) Comparing the write speed of each nanocomposite material with the simulated results of the Monte Carlo model.
presented here outperform this resist by a factor of approximately 14.

### 3. Conclusion

Three metal–organic negative tone electron beam resists have been investigated and we have demonstrated that the exposure sensitivity of the material can be increased by around three times by chemical design, that is, by introducing components such as diallylammonium and mercury dichloride in 3 while maintaining a high resolution of 15 nm half-pitch. The Monte Carlo simulations and experimental data are in excellent agreement, and suggest that the improvement in sensitivity is due to an increase in the generation of SEs and AEs within the resist. Comparing this study to previous studies, we have shown that

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**Figure 8.** XPS of resist 3 material before and after exposure to the electron beam.

**Figure 9.** The etch process in resists 1, 2, and 3 (a). Patterned 1 before the dry etching process, d) 1 after an 18 s pBosch dry etch process, g) Fins with an 8 nm width after removal of 1. b) Patterned 2 before the dry etching process, e) 2 after an 18 s pBosch dry etch process, h) fins with an 8 nm width after removal of 2. c) Patterned 3 before the dry etching process, f) 3 after an 18 s pBosch dry etch process, i) fins with an 8 nm width after removal of 3. The parameters of the process are gases: SF₆ and C₄F₈ with flow rates of 22 and 35 sccm respectively, the DRIE forward power is 20 W and the ICP forward power is 1200 W.
by understanding the exposure mechanism we have increased the resist sensitivity by a factor of 10. Preliminary studies show all three resists have an excellent etch performance which we conclude is due to the presence of $\text{CrO}_x\text{F}_y$ and $\text{NiO}_x\text{F}_y$ which are not reactive in an $\text{SF}_6$ and $\text{C}_4\text{F}_8$ plasma.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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