Low Acceleration Voltage Characterization of SML Electron Beam Resist for Ultra High Aspect Ratio Nano-Lithographic Applications

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Abstract

The performance of a new resist called SML 550 for use in of electron beam lithography has been investigated at Raith GmbH in Germany and at the University of Manchester. The thickness of the SML 550 resist was 677nm. Raith GmbH produced nano-structures with a high aspect ratio of 13.2:1 using an acceleration voltage of 30KV. The trench line width and height was approximately 43 and 568nm respectively. At the University of Manchester, The SML 550 resist achieved an aspect ratio of 14.7:1. This was fabricated using an acceleration voltage of 25KV. The trench line width and height was approximately 46 and 677nm respectively. This is significant, as this result cannot be achieved with the industry standard electron beam resist known as PMMA.

Keywords: SML series resist, Ultra high aspect ratio, electron beam resist, electron beam lithography.

1.0 Introduction

Poly(methylmethacrylate) (PMMA) is an organic electron beam resist well known to the scientific and industrial communities; it can produce features tens of nanometers in size [1]. However, to achieve such geometries, the resist film thickness must be around 40nm and hence, it has an aspect ratio limit of approximately 4:1 [2].

Due to the geometry of the polymer nanostructures, dry etching techniques such as inductively coupled plasma (ICP) and reactive ion etching (RIE) are preferable to transfer these nanoscaled structures to a substrate such as Silicon (Si) or Gallium Arsenide (GaAs). However, the etch rate of the semiconductor is much slower than the PMMA, which is problematic because the nano-scaled structures will not be etched deep into the substrate. As a result, transferring these nano-scaled structures with sub-10 nm geometries deep into the substrate cannot be achieved with standard PMMA resists.

If the thickness of the PMMA film is increased to hundreds of nanometers, then the resultant nano-scaled structures can be driven deeper into the substrate. However, as the incident electrons penetrate through the resist, they are scattered either elastically or inelastically in arbitrary directions away from the primary beam. As a result when the electrons clear the resist at this thickness, they may have been scattered tens to hundreds of nanometers away from the primary beam; this leads to large proximity effects, which cause the nano-scaled structures to collapse upon development. The generation of secondary electrons also contributes to the proximity effect; these electrons are scattered in arbitrary trajectories at distances over 1μm away from the primary beam. Fabricating sub-10nm structures cannot be achieved at this resist thickness.
In this investigation, a new electron beam resist called SML 550 was characterized at Raith GmbH in Germany and at the University of Manchester in U.K. The objective was to investigate the exposure clearing dose of the resist and to achieve the highest possible aspect ratio.

2.0 Experimental Details

2.1 Characterization of the SML 550 resist to determine the e-beam exposure dose

These SML 550 resist was spun onto 10mm×10mm silicon substrates. The resist was spun using a spin cycle of 4000rpm for 45 seconds which was followed by a soft–bake at 180˚C for 3 minutes, allowing the Anisole (which is the cast solvent for the SML series resist system) to evaporate.
The SML resist was exposed to the electron beam. This was achieved using a Raith 152, which was driven by a 20MHz pattern generator and a Camebridge S360 scanning electron microscope (SEM) which had a 300KHz Elphy Quantum pattern generator attachment. To determine the appropriate exposure clearing dose, when using the Raith 152 the exposure pattern consisted of a matrix of a single pixel lines. These lines were exposed with a dose scaled in incremental steps of 2500pC/cm, up to a highest dose of 3500pC/cm. Hence, the clearing dose could be accurately determined. In order for the pattern to be verified in the resist, the length of the lines needed to be 2mm so that the sample could be cleaved. The write field size of the pattern was 50μm and a series of these patterns were stitched together to form 2mm structures.
Before exposing the SML550 resist using the Camebridge S360 SEM the sample was cleaved first. This was done so that half of the exposure was written off the cleaved edge of the sample (as the camebridge S360 SEM does not have a laser stage to stitch multiple patterns together) so that the features written in the resist can be viewed at an angle of >45˚. The pattern was exposed in the resist, consisted of a matrix of 50nm by 200μm boxes. These boxes were exposed with an area dose scaled in incremental steps of 550 up to a highest dose of 660μC/cm^2 and the write field size was 200μm. The exposure parameters for both machines are given in table 1 – 0.

Exposure Parameters	Camebridge S360	Raith 152
Electron Source (Filament)	Tungsten	Thermal Field Emission
Step Size (nm)	3.052	2
Beam Current (pA)	16	22.5
Dwell Time (μS)	3	9.103
Voltage (KV)	25	30
Dose	550μC/cm^2	2500pC/cm
Working Distance (mm)	5	6.7

Table 1 – 0: Exposure parameters of the SML 550 resist.

Both of the samples were developed using solution of MIBK (Methyl IsoButyl Ketone) and IPA (IsoProPanol), in the ratio of 1:3, for 30s followed by a 20s rinse in IPA and blow dried using Nitrogen. The sample exposed using the Raith 152 tool was cleaved and post exposure baked at 90˚C for 10mins before being viewed at angle of 80˚, allowing the resist to harden, as it was found that the structure when being viewed wrapped and distorted. Once the post exposure bake was done, the sample was then sputter coated with 20nm of Platinum, allowing for the sample to dissipate the charge when being it was inspected.
150nm of Aluminium was thermally evaporated on to the sample that was written and developed at the University of Manchester. The sample was placed in a bath of Acetone for 14hrs in order for the lift off process to work. Once the Aluminium had lifted the sample was blow dried using Nitrogen.

3.0 Results

Figure 1 shows that the SML550 resist thickness was approximately 680nm and the pitch of the feature was 400nm. The image clearly shows that a clearing dose was not found using these exposure parameters. The trench had not cleared the resist by 112nm as the depth of the trench was 568nm. Closer inspection of the trenches showed that the line width of the feature was ~43nm, achieving an aspect ratio of 13.2:1.

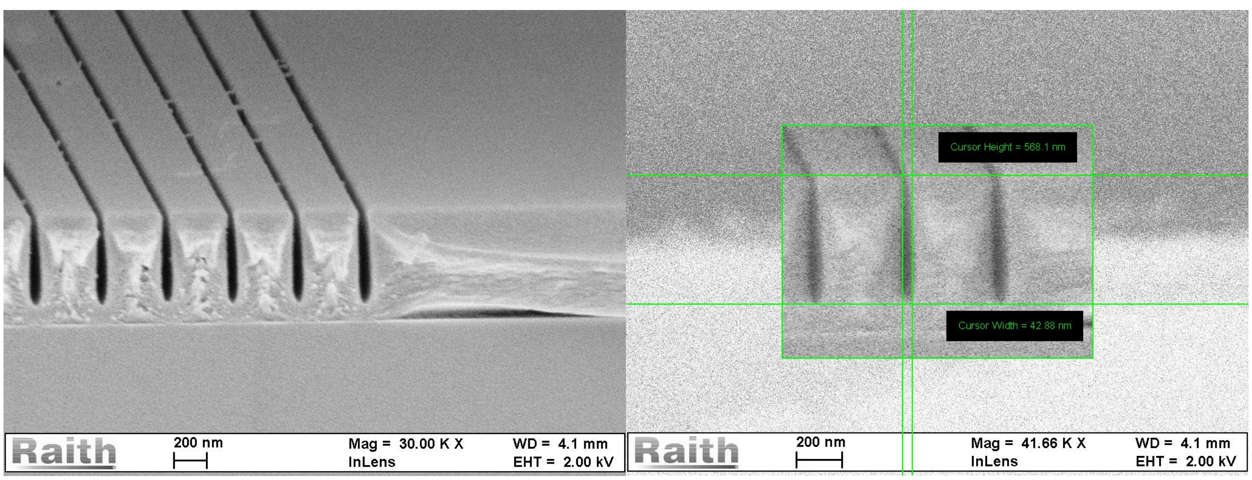

Figure 1: a, profile of the trenches written in SML550 resist viewed at an angle of 80˚, b, Close up view of the trenches seen in the left also viewed at an angle of 80˚.

The image of figure 1b shows that the side walls are straight. For the SML550 resist to produce these nano-structures, it is evident that the inelastic scattering and backscattered electron processes do not occur as frequent as it does at 30KV in conventional PMMA. This is due to the nature of the molecular properties of the SML series resist. This demonstrates that smaller feature sizes can be achieved by the SML550 resist by confining the forward scattering electrons to the incident beam inside the resist. However, a high exposure dose is required to clear the thickness of the resist. It is apparent that the SE does not occur as the 43nm line width has not been increased. Therefore, the proximity effects appear to be negligible.
Figure 2a shows that the thickness of the resist is 540nm, however this image was taken at an angle of 52˚. Therefore, taking this into account the resist thickness is 680nm. It can be seen that the features have cleared the resist. Therefore an aspect ratio of 14.7:1 has been achieved using a

tungsten filament. The image shows that the side walls of the trench are not straight like the features achieved in figure 1b.

Figure 2b shows Aluminium structures that were lifted off. The thickness of these structures was 100nm, and this was done to prove that the lift off process could be achieved at this geometry. The Aluminium structure seen here have a minimum line width of 60nm and the length was 25μm.

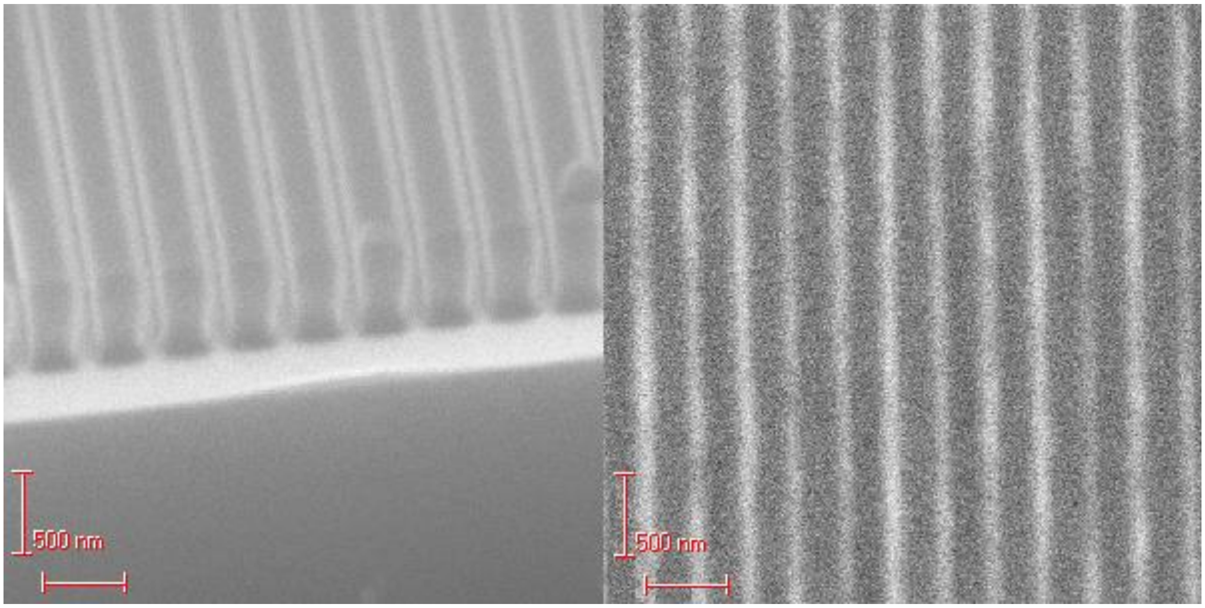

Figure 2: a, profile of the trenches written in SML550 resist viewed at an angle of 52˚, b, Top view of the Aluminium lines.

4.0 Discussion

Figure 3 shows an image of a HEMT device that was developed at the University of Manchester. It was fabricated using the SML series resist technology. It clearly shows the profile of the Titanium (Ti) / Gold (Au) Schottky gate contact to have an aspect ratio of 5.2:1 in metal as the dimensions of the gate is that the gate length was 104nm and the gate height was 540nm.

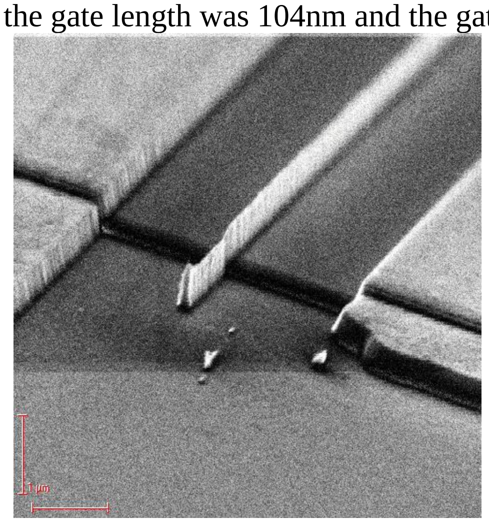
Figure 3: SEM image of a Schottky gate structure with an aspect ratio of 5.2:1.

Even though the dimensions achieved by the Raith 152 and Camebridge S360 tools are similar the straightness of the resist side walls are not. It is evident that the shape of the gate follows the shape of the resist (see figure 2a), where the side walls of the resist demonstrate that the electron beam spot produced by the Raith 152 has added benefits. The generation of SE have minimum effect where more secondary electronsare produced by the Tungsten filament. This is evident, because as the primary electrons (PE) penetrate further into the resist, the trench nanostructure width increases and this can be seen clearly in figure 2a. This is due to the electron beam spot size, the Raith 152 tool has a spot size of 1.5nm as the Camebridge S360 has a 6nm spot size.
Even though this is an added benefit for lift off, it is not desirable for dry etching. As straight walls are required and has been demonstrated in figure 1b. This is a significant result as the resist thickness is approximately 5.2 times larger than standard PMMA, when fabricating 43nm features, hence, these nano-structures will be etched 5.2 times deeper into the substrate.
Figure 4 shows the latest results of PMMA resist that was exposed at 100KV. The PMMA thickness was 1μm and the features were 80nm, therefore, the aspect ratio of 12.5:1 was obtained. Comparing this results with result depicted in figures 1 and 2, the aspect ratios achieved at the lower acceleration voltages with either source exceeds the limits of what can be achieved with PMMA using the higher acceleration voltages of 100KV.

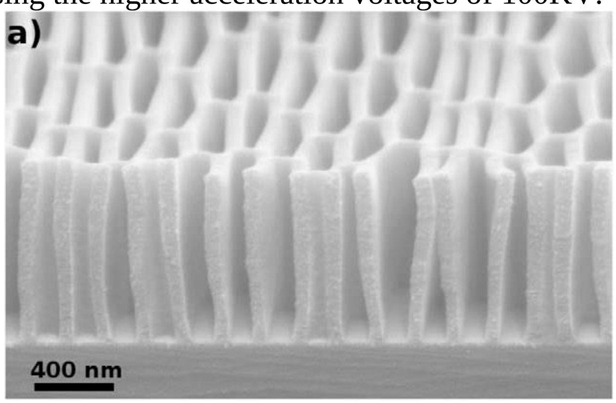

Figure 4: Scanning electron microscope (SEM) images of dense lines exposed in 1μm thick PMMA on Cr/Si substrate (tilt 70˚) exposed at 100KV [3].

5.0 Conclusion

An electron beam resist called SML550 has been investigated to produce a high aspect ratio at lower acceleration voltages of 25 and 30KV. The aspect ratio that was obtained was 14:1. It was found that this was 5 times larger than that of PMMA. It was clear that the SML550 did not suffer with these problems as the 43nm structures remained after the development process. Hence, the proximity effect was negligible.
Clearly the resist needs to be investigated further, more work needs to be done using the Raith tool. The exposure parameters need to be refined. The exposure current and dwell time needs to be investigated. Thermal Field Emission (TFE) tools such as the Raith 152, had a current density of approximately 100 times greater than that of the tungsten source. This means that more electron scattering events (secondary electrons and back scattered electrons) can occur inside the resist. Therefore, the current must be reduced to ~10 to 1pA and the dwell time increased. This will confine the electrons from spreading. The dose must not be increased, if it is then the width of the features will widen. Looking closely at the exposure parameters in table 1 – 0, it can be seen that the parameters used are very different. Using the Tungsten source, a clearing dose was

found at a lower acceleration voltage (25KV), these parameters used less current than the TFE source and the dwell time was decreased, however, the step size was increased in order to satisfy the dose equation. It is my recommendation that with the next set of exposures the parameters used by the Tungsten source should be used as a guide. Thus, decrease the current and dwell time and increase the step size.

It is evident that from the preliminary results from the SML resist technology has demonstrated comparable results with the latest results shown at higher acceleration voltages of 100KV, if not higher aspect ratio. It is the mission to demonstrate higher aspect ratio at lower acceleration voltages than can be done using 100KV.

6.0 References

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