# Helium Ion Beam Lithography on Fullerene Molecular Resists for Sub-10 nm Patterning

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As nanoelectronic device design pushes towards ever smaller feature sizes, there is an increasing need for new lithographic patterning techniques and resists. A new class of fullerene-based molecular resists are being developed to meet this need, taking advantage of a smaller molecular size to achieve higher resolution pattern definition for electron beam lithography (EBL) than conventional resists such as PMMA allow [1]. Recent EBL investigations with fullerene resists have demonstrated high resolution patterning, with a high sensitivity and low line edge roughness [2]. Furthermore, the resists exhibit high etch resistance, which is desirable for subsequent pattern transfer. Helium ion beam lithography (HIBL), an emerging technique that uses a sub-nanometer focused beam of helium ions generated in the helium ion microscope (HIM) to expose resist, promises to drive nano-patterning beyond the capabilities of conventional EBL [3,4]. Here we present the latest results from an investigation into HIBL with a novel fullerene-derivative molecular resist.

A fullerene derivative dissolved in anisole (HM-01, Irresistible Materials Ltd.) was spin-coated onto silicon wafers to a thickness of approximately 15 nm. Following a pre-exposure bake, the samples were exposed in a helium ion microscope (HIM, Zeiss Orion Plus) to a 30 keV focused helium ion beam. The samples were then developed in cyclohexanone to produce various negative tone patterns which were characterised using atomic force microscopy (AFM) and HIM.

To determine the limits of HIBL pattern definition in HM-01 resist, arrays of single pixel lines with pitches ranging from 44 nm to 10 nm were exposed over a range of doses from 0.005 to 0.1 nC/cm. Examples of HIM secondary electron images of the resulting patterns are presented in Figure 1 and individual lines are still resolvable with a 12 nm pitch (Figure 1 f)). The optimum dose for single pixel line arrays with pitches down to 14.5 nm was determined to be 0.06 nC/cm (Figure 1 b) and e)). The optimum dose was found to reduce for pitches below this range, possibly due to proximity effects, which, whilst significantly smaller than in conventional EBL, do become noticeable at these very small length scales. Continuous and well defined lines with a 17 nm pitch and a 0.5 mark-space ratio (line width of ~ 8.5 nm) were achieved as shown in the HIM image and corresponding contrast line profile in Figure 2. This is comparable to the best achievable with state-of-the-art EBL, despite being carried out using a tool not optimized for lithography. Area exposure of HM-01 resist using HIBL was also investigated: AFM characterisation on large area exposures resulted in the dose response curve shown in Figure 3, confirming negative tone behaviour with a sensitivity (50% of final full exposed thickness) of ~40 μC/cm$^2$.

Further process optimization and pattern transfer development are currently underway with the aim of providing a full assessment of the capabilities and limitations of HIBL in combination with molecular resists for next generation nano-patterning.

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[1] A. P. G. Robinson, R. E. Palmer, T. Tada, T. Kanayama, and J. A. Preece. Appl. Phys. Lett. 72 (1998) 1302.
[2] D. X. Yang, A. Frommhold, X. Xue, R. E. Palmer, and A. P.G. Robinson. J. Mater. Chem. C. 2. (2014) 1505-1512.
[3] D. Winston, B. M. Cord, B. Ming, D. C. Bell, W. F. DiNatale, L. A. Stern, A. E. Vladar, M. T. Postek, M. K. Mondol, J. K. W. Yang, and K. K. Berggren, J. Vac. Sci. Technol. B. 27 (2009) 2702–2706.
[4] V. Sidorkin, E. van Veldhoven, E. van der Drift, P. Alkemade, H. Salemink, and D. Maas, J. Vac. Sci. Technol. B. 27 (2009) L18-L20.

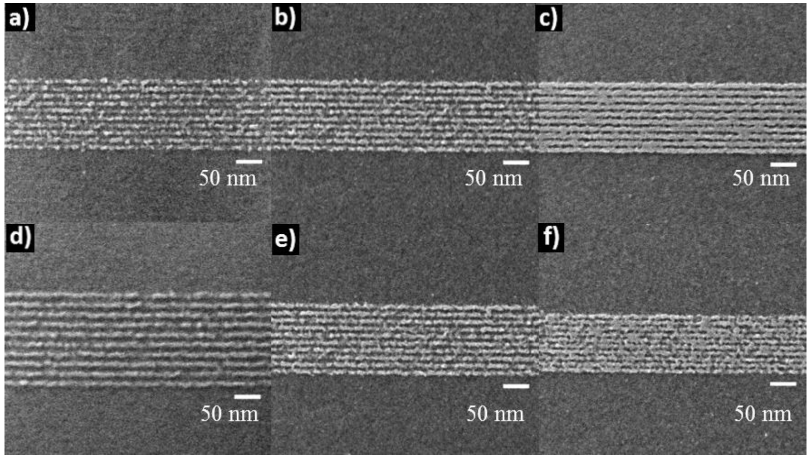


Figure 1. **a)-c)** HIM images show the effect of increasing the line dose at a fixed 14.5 nm pitch (line doses are **a)** 0.045, **b)** 0.06 and **c)** 0.09 nC/cm); **d) – f)** HIM images show the effect of decreasing the pitch at a fixed line dose of 0.06nC/cm (pitches are **d)** 19, **e)** 14.5 and **f)** 12 nm).

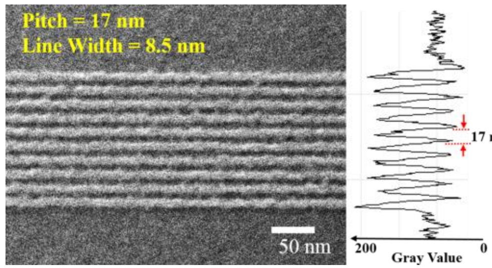


Figure 2. Left: HIM image of dense single pixel features exposed at 0.09 nC/cm on ultra-thin HM-01 resist. Right: SE contrast measurement reveals that 17 nm pitch and 8.5 nm line width were achieved in the resolved lines.

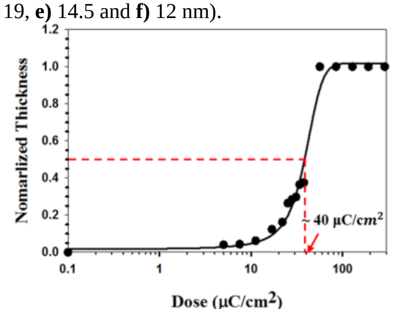


Figure 3. Dose response curve for novel fullerene resist HM-01. The sensitivity is measured to be 40 μC/cm$^2$.