The potential of negative-tone PMMA e-beam lithography to enhance superconducting nanowire applications

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In recent decades, negative-tone resists such as Hydrogen Silsesquioxane (HSQ) have become strong candidates for high-resolution electron-beam lithography, because of their small line edge roughness, high etching resistance, and small molecular size [1]. However, negative electron-beam resists have higher requirements in terms of process conditions and surface quality. Despite more difficult processing requirements, negative electron-beam resist remains a promising path for producing sub-100 nm nanowires. As an alternative, a positive-tone electron-beam resist, Poly-methyl-methacrylate (PMMA), can be used as a negative resist for patterning of ultra-narrow nanowires [2]. At high exposure doses ($\geq$1 mC/cm^2), PMMA chains decompose into very short low-molecular-weight fragments, which start to form a dense carbonized film (Fig. 1a).

In our experiment, we performed comparative experimental investigation of superconducting nanowire single-photon detectors (SNSPDs) (Fig. 1b) based on superconducting niobium nitride (NbN) nanowires with sub-micrometer size. We have found that devices prepared using negative-tone PMMA (dose of 10 mC/cm^2) demonstrate improved performance metrics over those prepared using positive-tone lithography with the same PMMA resist. The critical current density (j_c) of negative-tone PMMA SNSPDs was 30% higher (Fig. 2) than the j_c of positive-tone PMMA detectors with identical geometry [3]. The observation of higher count rates and saturation of internal efficiency (the probability that the absorption of a photon creates a detection pulse) at 780 nm measured at 4.2 K for the negative-tone process suggests that the critical current of negative-tone devices approaches the theoretical limit of current in nanowires more closely than the positive-tone devices. The higher critical current density of the negative-tone devices is expected to also result in decrease of the minimal detectable energy of photon.

[1] A. E. Grigorescu and C. W. Hagen, *Nanotechnology* 20, 292001, 2009.
[2] I. Charaev *et al*, *J. Appl. Phys* 122, 083901, 2017.
[3] I. Charaev, *arXiv*:1811.05192 [physics.app-ph], 2018.

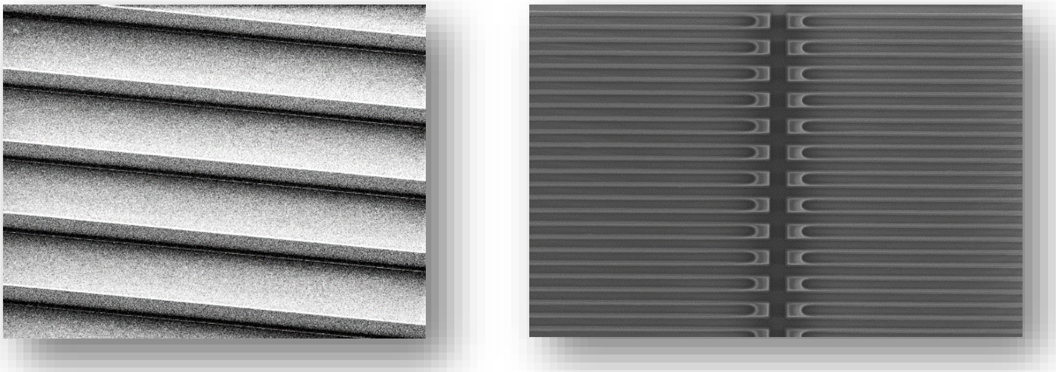

Figure 1. a) Narrow superconducting nanowires made by negative-tone PMMA resist.
b) A meander-shape superconducting nanowires single-photon detector.

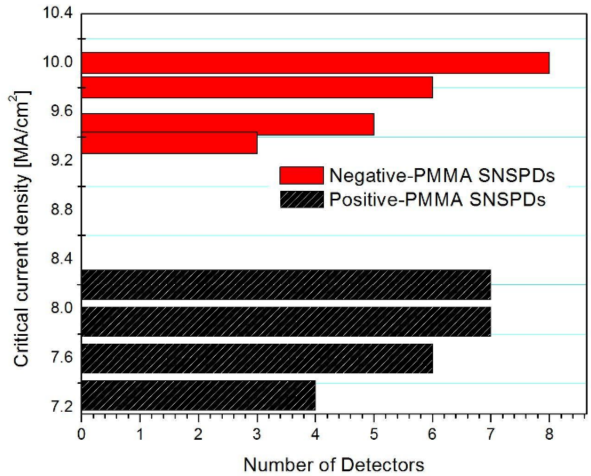

Figure 2. The statistical distribution of critical current density of SNSPDs made by positive- (black) and negative-tone PMMA (red) lithography.

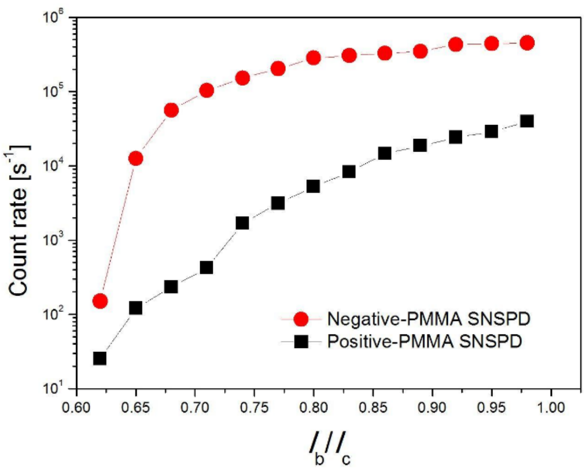

Figure 3. The count rate as a function of the relative bias current at 780 nm wavelength for positive- (black squares) and negative-tone PMMA (red circles) SNSPD.