Fabrication of Tunnel Junctions for Direct Detector Arrays With Single-Electron Transistor Readout Using Electron-Beam Lithography

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***Abstract*—This paper describes the fabrication of small aluminum tunnel junctions for applications in astronomy. Antenna-coupled superconducting tunnel junctions with integrated single-electron transistor readout have the potential for photon-counting sensitivity at sub-mm wavelengths. The junctions for the detector and single-electron transistor can be made with electron-beam lithography and a standard self-aligned double-angle deposition process. However, high yield and uniformity of the junctions is required for large-format detector arrays. This paper describes how measurement and modification of the sensitivity ratio in the resist bilayer was used to greatly improve the reliability of forming devices with uniform, sub-micron size, low-leakage junctions.**

***Index Terms*—Deep ultraviolet, electron-beam lithography, PMMA/copolymer, single electron transistor, SQUID.**

I. INTRODUCTION

TO TAKE advantage of low background photon rates, space-based submillimeter-wave interferometers will require advances in detector sensitivity and speed. Integration of photon-counting detectors with low power readout electronics to make large-format arrays is desired [1]. Antenna-coupled superconducting tunnel junction detectors have the potential for photon-counting sensitivity at sub-mm wavelengths [2]. The device, a "single quasiparticle photon counter" (SQPC), consists of an antenna to couple radiation into a small superconducting volume and cause quasiparticle excitations, and a radio frequency single-electron transistor (RF-SET) [3] to measure currents through tunnel contacts to the absorber volume.

The small tunnel junctions required both for the detector and for the SET readout amplifier may be made simultaneously by use of electron-beam lithography and the double-angle deposition process first used to fabricate SET's [4]. This paper describes results on adapting standard SET fabrication techniques with the goal of producing SQPC and RF-SET devices with high yield, uniformity, and reproducibility for detector arrays.

Fulton and Dolan [4] made aluminum SET's using an offset mask technique [5], [6] in which electron-beam lithography on a bilayer resist [7] forms free standing bridges of polymethylmethacrylate (PMMA) atop a copolymer of methyl methacrylate (MMA) and methacrylic acid (MAA). Deposition of aluminum by evaporation at two different angles with an intervening oxidation step forms self-aligned tunnel junctions underneath the PMMA bridge with junction areas as small as 30 nm $\times$ 30 nm.

We have encountered two problems in applying the above basic fabrication technique to making arrays of SQPC detectors. The first is variability in the resist preparation-exposure-development process that causes unacceptable scatter in junction size and resistance. The second is a conflict between the desired resist properties for making both junctions and SET input gates. An SET can be a very high performance electrometer with nearly quantum-limited sensitivity [8]; however, for application as a detector readout amplifier, a sensitive voltmeter is needed with strong input coupling [9]. This is accomplished by adding to the SET a relatively large ($\approx$0.5 fF) input gate capacitor with an interdigitated finger geometry. As pointed out in [7], whereas the bilayer resist is ideal for producing large undercuts and suspended structures, it is not really appropriate to making densely packed features, such as the finger capacitor, because of difficulty in maintaining sufficient support to avoid collapse.

We describe here how we used the technique of pre-exposing the copolymer layer with deep ultraviolet (DUV) radiation [10], [11] to address both of the above problems. Whereas [10] and [11] used DUV exposure to increase the sensitivity of the copolymer layer enough to ensure sufficient undercuts for forming SET junctions, we used the process to tune the sensitivity of the copolymer to reach an optimum compromise between reliability of junction and finger capacitor fabrication. Our measurements then also gave us the capability to guard against and eliminate variability in the copolymer sensitivity.

First we present our technique and results for quantifying the response of the copolymer to electron and DUV exposure. We then describe the improved statistical yield and uniformity we obtained after using the response data to optimize the fabrication of SQPC and RF-SET devices. Finally, we show current-voltage characteristics for representative SQPC and RF-SET devices that we have made.

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II. RESIST RESPONSE

A. Measurement Technique

In our work, we have used independent developers for the PMMA and copolymer layers [12], and have, except for the DUV pretreatment, followed the specific resist preparation and development procedures used at Chalmers University for SET fabrication [13]. We used resist thicknesses of 400 nm (copolymer) and 60 nm (PMMA). The electron-beam writing was done, at 30 keV with a tungsten filament, in a Cambridge S240 SEM using the Nabity lithography system [14] in the Detector Development Laboratory at Goddard Space Flight Center, and at 50 keV with a LaB_6 filament in a JEOL JBX-5DII in the Nanoelectronics Processing Facility at the Naval Research Laboratory. The substrates used were thermally oxidized silicon wafers, which had gold contact pads, and rf resonant circuits for the RF-SET's [15], defined by optical lithography in advance of the e-beam and double-angle fabrication steps.

To measure the response of the resist layers to electron exposure, we wrote patterns of parallel single-pass lines spaced by 8 μm with doses ranging from 1 to 20 nC/cm. The ordering of the doses was arranged so that any slight proximity effect on the results for each line would be similar.

After development, the chips were cleaved through the resist patterns, coated with $<$10 nm of Au, and then inspected in our 30 keV SEM (see Fig. 1). We measured the width of the copolymer lines at the intersection of the cleaved surface with the substrate, and the width of the PMMA on the surface some distance away from the cleavage plan. This was done to avoid errors from distortion of the resist by the cleavage process.

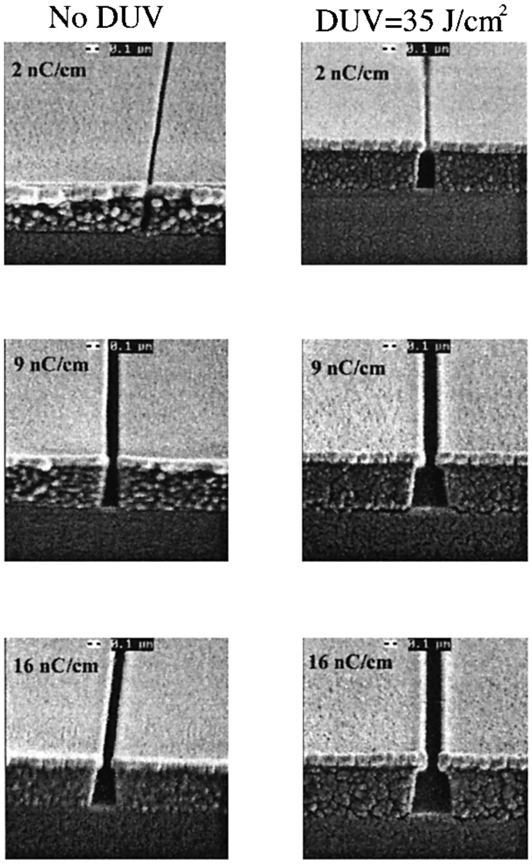

Fig. 1. Scanning electron micrographs of cleaved resist samples written at 50 keV, viewed nearly edge-on. In each image: cleaved substrate is at bottom, cross-section of developed copolymer/PMMA bilayer spans middle, and top surface of the PMMA slopes away at top. Left column shows results for various electron line doses without DUV pre-exposure. At right are corresponding results at 35 J/cm^2 DUV dose.

B. Response Curves

Fig. 2 shows the results of our measurements of the copolymer resist response to electron-beam exposure and development, both when untreated with DUV, and when treated with various DUV doses ranging up to 35 J/cm^2. The measurements were repeated both at 30 keV and 50 keV beam energies, and in one case with the temperature of the copolymer developer solution increased from 17 C to 22.5 C.

The line widths w between 100 nm and 600 nm exhibit a power-law dependence on the electron-beam line dosage D of the form $w = (D/a)^{0.45}$. The power-law behavior we observe indicates that the dominate energy deposition mechanism at the relevant distance scale in our resist system is the generation and scattering of fast secondary electrons [16]. We did not investigate line doses high enough to see the effects of long-range scattering of electrons in the substrate, and only for 50 keV writing on untreated resist did the line widths become small enough for other effects to cause deviations from the power-law.

To obtain the same copolymer line width with writing at 50 keV as at 30 keV, when keeping the DUV dose fixed, required a much greater increase in the line dose than expected from the change in the energy loss of the incident primary electrons per unit distance traveled. Instead of scaling the doses by 50/30, a factor of 4.5 was needed. The energy dependence of the forward scattering of the incident electrons, and the spatial distribution of secondary electrons, in our relatively thick resist layer significantly affect the depth of the undercut.

However, since the physical effect of the DUV exposure on the copolymer is to cause chain scission events just as in electron-beam exposure [17], we expected the reduction in the threshold-deposited-energy, required to cause the copolymer to develop, to be independent of the electron-beam energy later used. The inset to Fig. 2 shows the resist development threshold, relative to copolymer with no DUV treatment, calculated as the ratio of the coefficient a to its value without DUV exposure at the same beam energy. In terms of this measure, applying a DUV dose of 35 J/cm^2 increased the resist sensitivity by the same amount, a factor of 3, for exposure at either 30 keV or 50 keV.

III. DEVICE FABRICATION RESULTS

After measuring the response of the copolymer to electron-beam line-exposure, and the change in the resist sensitivity with DUV exposure, we were able to optimize our choice of electron-beam doses to best fabricate our detectors and readout amplifiers. Since we wish to fabricate integrated systems with a variety of resist geometries (free-standing PMMA bridges for junctions of various sizes, together with densely packed

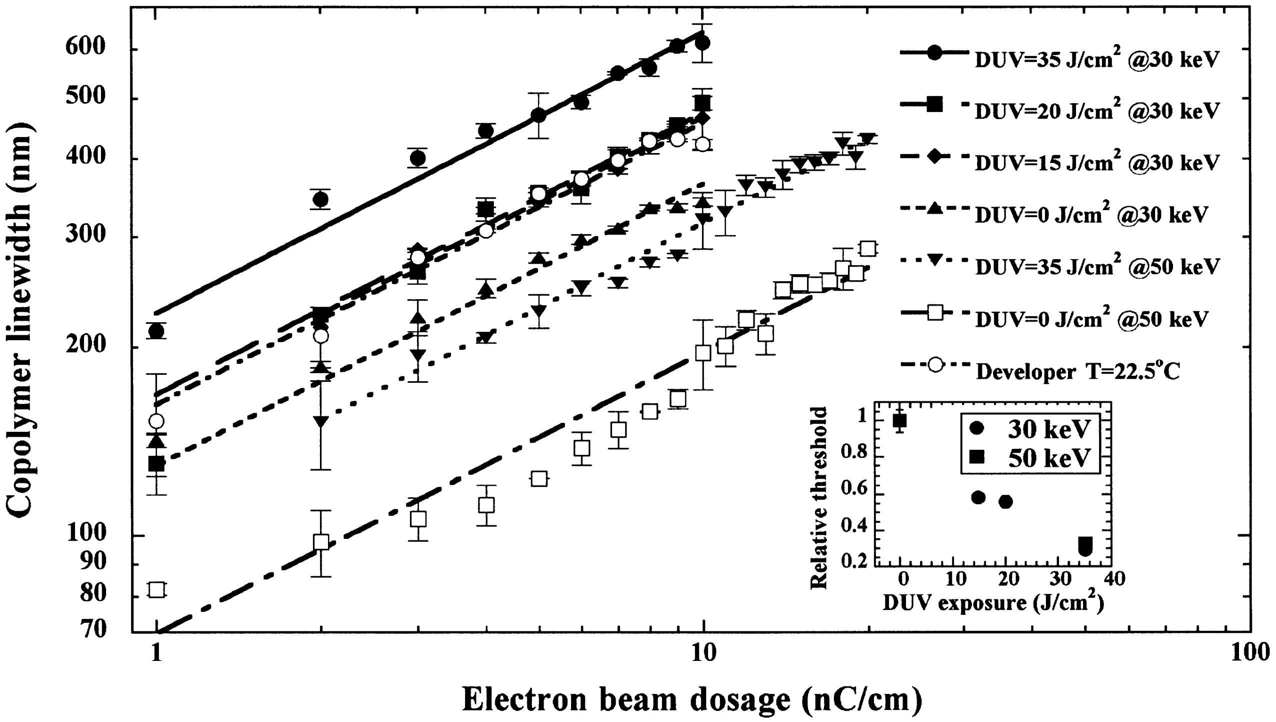

Fig. 2. Measurements of copolymer line full-width versus electron-beam line dosage for patterns written at 30 keV of 50 keV beam energy. Copolymer developer temperature was 17 C execpt for one sample written at 30 keV and developed at 22.5 C. Inset shows derived exposure threshold of the copolymer (relative to untreated resist) for various DUV doses.

TABLE I
DEVICE YIELD AND JUNCTION AREA VARIABILITY

	Junction area (nm^2)	Yield	Junction area variability within a field (σ)			Junction area variability over chips (σ)		
			Min	Median	Max	Min	Median	Max
Big gap devices	68 × 68	68%	2.6%	4.6%	24.3%	5.2%	26.9%	40.2%
Small gap devices	75 × 75	78%	2.0%	11.7%	72.4%	9.1%	32.0%	49.6%

meanders for capacitor fingers), using the DUV method to tune the copolymer sensitivity to the best value for a given writing energy was very helpful.

A highly sensitive copolymer layer works well for making PMMA bridges but leads to problems with the large gates. A low sensitivity layer gives reliable gate fabrication, but requires electron-beam doses around the bridges that are so high as to degrade the PMMA resolution. Before taking advantage of the DUV process, yields were very low.

In addition, repeated calibration of the resist sensitivity allowed us to improve the reproducibility of the fabrication because changes in resist sensitivity due to preparation, storage, or development conditions could be detected.

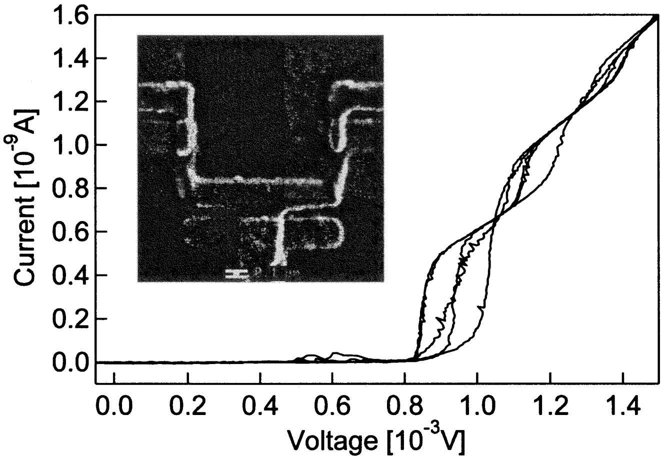

Fig. 3. Current-voltage characteristics, at four different gate settings, for a 600 kΩ SET fabricated with the DUV method. The device had a 315 aF gate capacitance, and a charging energy of 1.1 K. Inset shows SEM image of the source/drain contacts of a similar device from the same chip and writing field.

Table I summarizes the yield, uniformity, and reproducibility we were able to obtain with the optimized fabrication process at 50 keV. On our 8 mm × 10 mm substrates, the writing was organized into four 320 μm × 320 μm fields. In each field, we typically wrote arrays of 4 or 5 SET's with gates of various sizes connected in parallel to one detector. There were two SET arrays in each field, which had different designs for the width of the PMMA bridge (nominally 100 or 150 nm). The gate capacitors had 250 nm wide lines and spaces, with finger lengths 1.5–3.1 μm. Table I provides statistics on these two types of SET devices, with the bridge width denoted as "big gap" or "small gap."

On each substrate, we used a combination of junction resistance measurements and SEM imaging to determine a resistance-area product (230 to 630 $\Omega \cdot \mu\text{m}^2$) for tunnel barriers on that chip. Then, for each SET that was neither open nor short circuit, we calculated an effective junction area from its resistance. Out of a possible 50 big and 60 small gap devices, our yields were 68% and 78%, respectively. Uniformity of the junction areas was as good as 2% within a given field, and half the time was better than 5% or 12% for the big or small gap designs. The reproducibility of the junction areas over the four fields of

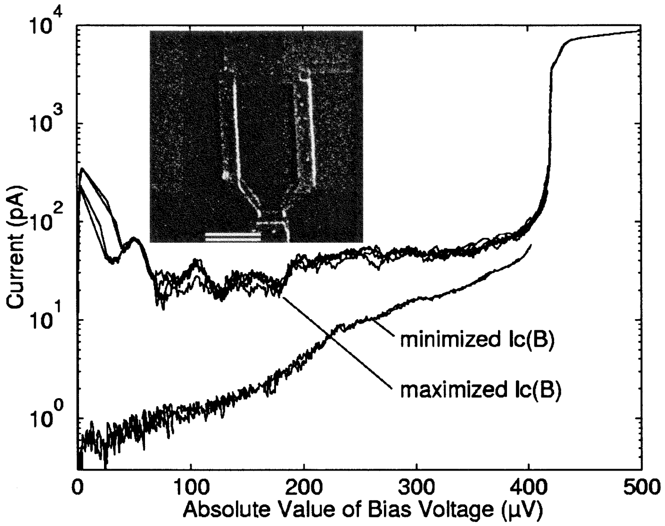

Fig. 4. Current-voltage characteristics of a prototype SQPC detector (without antenna structure) at 256 mK for two different applied magnetic fields. The 60 nm × 80 nm junctions had a $44\ \mathrm{k}\Omega$ parallel resistance in the normal state.

a chip was less good, with the median one-sigma variation over a chip being $\approx$30%, party due to variation in focus quality between fields. The junction reproducibility we obtained is similar to that reported in [10], but our process simultaneously produced large gate capacitors with high yield.

Figs. 3 and 4 show examples of the characteristics of SET and SQPC devices we have made. In the detector, two junctions in parallel form a superconducting quantum interference device (SQUID). An external magnetic field is used to suppress excess dark current caused by the effects of Josephson oscillations. From a measured dark current of 0.5 pA and a $30\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$ SET noise, we infer an electrical noise equivalent power $\approx 1.2 \times 10^{-19}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$ [18].

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