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Direct-Write X-ray Nanopatterning: A Proof of Concept Josephson Device on $Bi_2Sr_2CaCu_2O_{8+\delta}$ Superconducting Oxide

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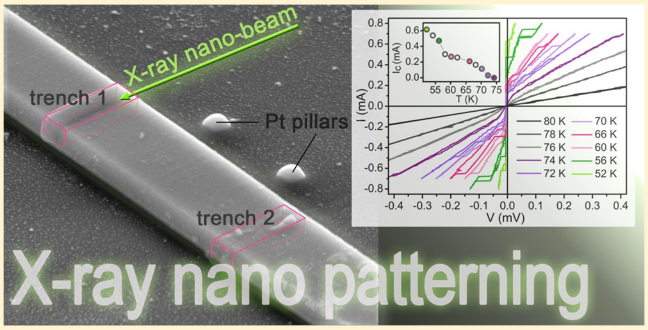
S *Supporting Information*



ABSTRACT: We describe the first use of a novel photoresist-free X-ray nanopatterning technique to fabricate an electronic device. We have produced a proof-of-concept device consisting of a few Josephson junctions by irradiating microcrystals of the $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) superconducting oxide with a 17.6 keV synchrotron nanobeam. Fully functional devices have been obtained by locally turning the material into a nonsuperconducting state by means of hard X-ray exposure. Nano-XRD patterns reveal that the crystallinity is substantially preserved in the irradiated areas that there is no evidence of macroscopic crystal disruption. Indications are that O ions have been removed from the crystals, which could make this technique interesting also for other oxide materials. Direct-write X-ray nanopatterning represents a promising fabrication method exploiting material/material rather than vacuum/material interfaces, with the potential for nanometric resolution, improved mechanical stability, enhanced depth of patterning, and absence of chemical contamination with respect to traditional lithographic techniques.

KEYWORDS: *nanopatterning, X-ray nanoprobe, synchrotron radiation, high-temperature superconductors (HTSC), Bi-2212, intrinsic Josephson junctions*

In microelectronics, the minimum feature size has gradually moved from the micro- to the nanodomain, and mass production of processors at the 14 nm technological node has recently started.[1,2] This quest for improved device performance has stimulated the development of several lithographic techniques. In this respect, the success of the approaches based on photolithographic processes has been based on the exploitation of light sources with shorter and shorter wavelengths, down to the 193 nm ArF lasers, representing the present standard for high volume production. At the moment, the use of shorter wavelengths is still the subject of intense research efforts. Extreme ultraviolet (EUV) lithography exploiting $\lambda = 13.5$ nm is considered a good candidate for sub-20 nm technological nodes and indeed has already shown the capability to produce patterns with resolutions down to 8 nm half-pitch in its interference version,[3] even though many problems still have to be solved about the power of the light sources[4] and the resist resolution.[5]

Concerning radiation with $\lambda \lesssim 1$ nm (i.e., in the realm of X-rays) remarkable results have been obtained in the field of micromachining by means of the LIGA process.[6] Fully functional static random access memory (SRAM) devices with 250 nm minimum feature size have also been fabricated by X-ray lithography,[7] using the conventional mask-based approach. Due to the fact that mask fabrication is very challenging, maskless methods could represent an interesting alternative. However, lab-scale sources presently show severe limitations in terms of X-ray flux and beam size;[8] therefore, much work has been based on the exploitation of synchrotron radiation sources. For instance, hard X-rays have been proved to promote the growth of ZnO crystallites from sol-gel films obtaining well-defined patterns,[9] and continuous lines with

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