

Doping Change in the Bi-2212 Superconductor Directly Induced by a Hard X-ray Nanobeam

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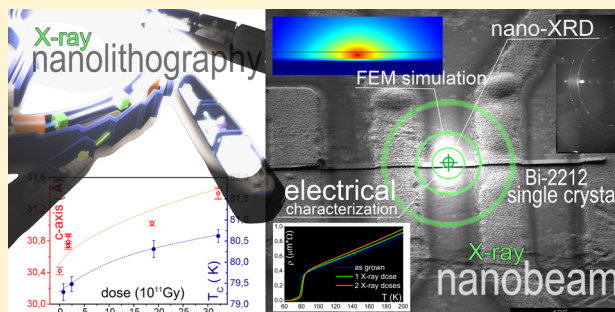
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Supporting Information

ABSTRACT: We describe the controlled use of a 17 keV X-ray synchrotron nanobeam to progressively change the oxygen doping level in Bi-2212 superconducting whisker-like single crystals. Our data combine structural and electrical information collected on the same crystals, showing a maximum change in the critical temperature T_c of 1.3 K and a maximum elongation of ~ 1 Å in the c -axis length, compared to the as-grown conditions. Simulations of our experimental conditions by means of a finite element model exclude local heating induced by the X-ray nanobeam as a possible cause for the change in the doping level and suggest an important role of secondary electrons. These findings support the possible use of hard X-rays as a novel direct-writing, photoresist-free lithographic process for the fabrication of superconducting devices, with potential nanometric resolution and 3D capability.

KEYWORDS: High-Temperature Superconductors, Bi-2212, single crystal, doping, nanolithography, X-rays nanobeam, whiskers



In the past few decades, the goal of achieving higher speed and lower power consumption has driven the semiconductor industry to design and produce smaller and smaller integrated circuits. This trend has stimulated deep innovation in the lithographic techniques, setting for instance the 193 nm immersion technology as the present standard for the 32 nm node.¹ However, further decrease in half-pitch size down to 22 nm has been made possible thanks to the development of a technique based on extreme ultraviolet (EUV) radiation with much shorter wavelength ($\lambda = 13.5$ nm), which in its preproduction implementations was provided by synchrotron radiation facilities.^{2,3} Nevertheless, the run toward the use of ever shorter radiation for integrated circuits has come to a pause, since the development of lithographic processes exploiting hard X-rays with $\lambda \approx 0.1$ nm has been hindered by problems related to the fabrication of suitable masks with both high enough contrast in their absorbing power and small enough features.¹ Although some improvements have been suggested via the demagnification effect induced by near-field Fresnel diffraction,⁴ it is in the field of microelectrical-mechanical systems (MEMS) that hard X-ray lithography has

shown its full potential with the introduction of the so-called LIGA process.^{5,6}

All of the above-mentioned techniques are based on photoinduced chemical modifications of the photoresist layers covering the substrates, which imply the subsequent introduction of both a development and an etching stage in the fabrication process. In parallel, some direct-writing techniques have been developed to modify substrate properties without photoresists. Among them, the focused electron-beam⁷ and the focused ion-beam-induced deposition and etching,⁸ along with the scanning probe lithography,⁹ are the most well-known; all of these techniques enable nanometric spatial resolution. Concerning X-ray direct-writing lithography, a few examples have been recently reported.^{10–14} Although the use of synchrotron radiation nanoprobe has allowed spatial resolutions down to ~ 25 nm,⁴ in all previous cases patterning was limited to organic or organometallic materials. Since these

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