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Atom-by-Atom Analysis of Rare-Earth Dopants implanted in Silicon

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Rare-earth doped materials occupy a crucial place in optoelectronics, and are already deployed in devices such as fiber amplifiers and solid-state lasers [1]. Optical properties of such systems arise from the partially filled 4*f*-electron shell of the rare earth (RE) atoms which is screened by the more extended 5*s* and 5*p*-orbitals. This results in sharp optical spectra whose shape and emission wavelength are not strongly affected by the host. For RE-doped semiconductors, photo- or electro-luminescence is possible when energy transfer from the host to the dopant occurs. Interest in doping silicon with RE atoms has consequently been driven by potential applications in Si photonics [2] that would be compatible with current CMOS technologies. Several hurdles persist, however, in the implementation of Si:RE light emitting devices. Amongst the major problems are the low solubility of RE in silicon and the multiplicity of optical centers that RE atoms form when inserted in Si.

In this work, we study the implantation of cerium atoms into silicon, as well as the distribution of the dopants following a thermal annealing process. By imaging individual dopants (Fig. 1(a)) using aberration-corrected scanning transmission electron microscopy (FEI-Titan 80–300 operated at 300 kV and equipped with two CEOS correctors), the dopant penetration depth can be directly evaluated and compared to the extent of the damage created in silicon. As observed from Figure 1(b), the visibility of Ce atoms in amorphous Si is better than in the crystalline Si region. Channeling of incident electrons are responsible for the increased intensity contribution of Si columns, and represents one of the challenges for single atom imaging in a crystalline matrix [3, 4]. In this study, a few dopants can be detected deeper below the a-Si/c-Si interface, and these dopants are found to occupy interstitial sites (Fig. 1(c) and (d)). As demonstrated in multislice simulations [5], the relative intensity of individual dopants with respect to silicon columns will depend on the position of the Ce atom along the optical axis and on the defocus (Fig. 2). After an annealing process, the a-Si recrystallized, and we observed clustering of dopants in Si and partial segregation of the dopants to the surface, which is consistent with the low solubility of Ce in Si. Methods to increase the visibility of single atoms and clusters embedded in a crystalline matrix will be presented.

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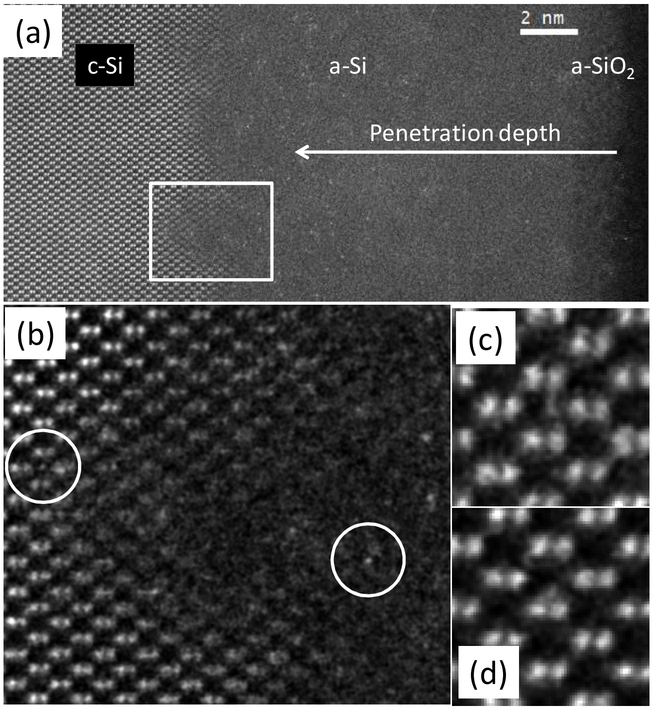

FIG. 1. (a) Cross-sectional ADF-STEM image of cerium dopants implanted in silicon (20keV, 3x10^{14} atoms/cm^2). (b) Close-up of the region shown in (a) where circles indicate the location of two individual dopants. (c) and (d) ADF-STEM images of dopants located deeper below the a-Si/c-Si interface. Low-pass Butterworth filters were applied to (b), (c), and (d), and the images are displayed with a non-linear intensity scale. The top surface is located on the right of the images.

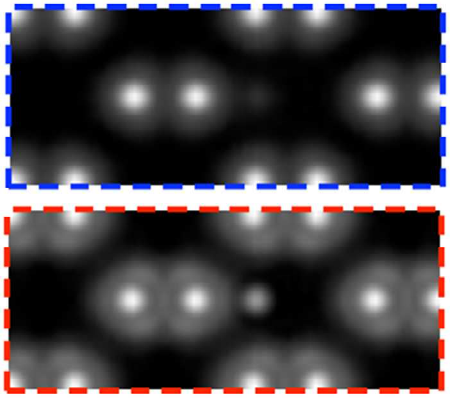

FIG. 2. Multislice simulations of an interstitial Ce atom inserted in a Si crystal. The depth of the Ce is 8 nm and the specimen thickness is 16 nm. The defocus is 8 and 12 nm, respectively, for the top and bottom images.