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An upper limit on the lateral vacancy diffusion length in diamond

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ABSTRACT

Ion implantation is widely used to modify the structural, electrical and optical properties of materials. By appropriate masking, this technique can be used to define nano- and micro-structures. However, depending on the type of mask used, experiments have shown that vacancy-related substrate modification can be inferred tens of micrometers away from the edge of the mask used to define the implanted region. This could be due to fast diffusion of vacancies from the implanted area during annealing or to a geometric effect related to ion scattering around the mask edges. For quantum and single-atom devices, stray ion damage can be deleterious and must be minimized. In order to profile the distribution of implantation-induced damage, we have used the nitrogen-vacancy color center as a sensitive marker for vacancy concentration and distribution following MeV He ion implantation into diamond and annealing. Results show that helium atoms implanted through a mask clamped to the diamond surface are scattered underneath the mask to distances in the range of tens of micrometers from the mask edge. Implantation through a lithographically defined and deposited mask, with no spacing between the mask and the substrate, significantly reduces the scattering to ≤5 μm but does not eliminate it. These scattering distances are much larger than the theoretically estimated vacancy diffusion distance of ~260 nm under similar conditions. This paper shows that diffusion, upon annealing, of vacancies created by ion implantation in diamond, is limited, and the appearance of vacancies many tens of micrometers from the edge of the mask is due to scattering effects.

1. Introduction

Ion implantation into a solid matrix is an important technology that can be used to modify the structural, optical and electronic properties of materials [1]. Where precise positioning of the ions is required, such as in high precision semiconductor and single atom device fabrication [2,3], it is common to perform the implantation through a mask. Interaction of energetic ions with crystalline solids often results in the creation of vacancies, which can exist in isolation, as aggregates of two or more vacancies or as complexes with atoms. Such complexes can change the local potential landscape, leading to non-uniform device performance. For these reasons it is important to quantify the damage profiles obtained from ion implantation even down to the single vacancy level, especially for nanoscale quantum devices. In particular, assessing the distribution of vacancies with respect to the irradiated regions (mask edge) during the implantation process and after thermal annealing is of paramount importance. The presence of vacancies away from the implanted region (mask edge) could potentially arise from one or both of two processes. First, vacancies created within the implanted region could possibly diffuse out of the implanted region upon annealing, or alternatively, impinging ions scattered from the mask edges could result in the presence of vacancies far away from the implanted edge. We find here that the second scenario becomes more prominent as the gap between the mask and the substrate increases.

A number of studies have reported on the diffusion of atomic species as well as vacancies in diamond. For example, boron, oxygen, nitrogen and lithium have been reported to diffuse over distances of the order of 500 nm at temperatures of 860 °C [4]. Studies on diffusion of vacancies in diamond have provided conflicting estimates of the diffusion lengths, ranging from a few hundred nanometers in the vertical direction [5] to tens of micrometers in the lateral direction [6–8]. In

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