

Effect of magnetic field on the nano-hardness of monocrystalline silicon and its mechanism

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The magneto-plastic effects observed of ionic crystals and semiconductors caused the research interest to them. It is generally accepted that the dominating mechanism of the variations in the mobility of dislocations, which are caused by an applied magnetic field, is the spin-dependent changes of the state of structural defects [1–7]. And the possible mechanism of the magnetoplastic effects of ionic crystals has been appropriately described [8, 9]: once a spin-selective nanoscale reactor is formed by electron transfer from the dislocation to the stopper, the Coulomb interaction that holds the dislocation pinned at the stopper is "switched off", and the spin-selective nanoscale reactor is in the singlet state; magnetic field stimulates conversion from the singlet to the triplet state, so that the reverse transfer is forbidden by spin selection rules; therefore the system with switched-off Coulomb potential has a longer lifetime, which implies higher depinning rate and increased dislocation mobility. The details of magnetically stimulated variation of mechanical properties and defect state of semiconductors haven't been sufficiently studied.

In this work the nano-hardness was chosen as a character of dislocation mobility, and the effects of magnetic field on the nano-hardness of monocrystalline silicon doped with phosphorous by ion implantation was studied. It is found that an applied magnetic field can increase the nano-hardness of monocrystalline silicon doped with phosphorous by ion implantation, and this increase can be eliminated by annealing the silicon crystals at 800 °C for 780 s. For the crystals that have not been exposed to a magnetic field, annealing them at 800 °C for 780 s cannot significantly affect their nano-hardness, but exposing them to the magnetic field mentioned previously can no longer affect their nano-hardness after annealing.

The mechanism of the effects was also investigated. It's established that an applied magnetic field can initiate the disbanding of vacancy clusters, which can cause a large number of nonequilibrium vacancies. And in the loading process of nano-indentation, the separated vacancies bind to adjacent dislocations produced by nano-indentation under the attraction of the half-planes of atom, resulting in dislocation climbing. The dislocation segments that have climbed get out of the slip plane, thus they are hard to slip, and as a result the pinning of dislocations is enhanced, therefore the nano-hardness is increased. The annealing applied in this work can eliminate the separated noneuilibrium vacancies in large qualities, thus the increase in nano-hardness caused by magnetic treatment can be eliminated by annealing (Fig. 1a). And the annealing can reduce the size of the vacancy clusters and maybe partially eliminate them, thus the subsequent magnetically stimulated vacancy cluster disbanding effect is significant weakened or even eliminated, thereby the magnetic treatment cannot significantly affect the nano-hardness any longer (Fig. 1b).

A possible mechanism of the magnetically stimulated disbanding was put forward: applied magnetic field convert electron pairs (Si-Si bonds thermally excited into singlet state) into triplet state rifely, and the life of triplet state is much longer than that of singlet state, thus the proportion of the electron pairs in excited state is increased, therefore the bond-breaking efficiency is increased and atoms are easier to migrate. This mechanism may also be applicable for magnetoplastic effect, since the depinning and slipping of dislocations are essentially achieved by atom migration (among adjacent sites). In essence, for ionic crystals, this expression is the same with the expression mentioned in the 1-st paragraph, but the expression here is also applicable to covalent crystals such as silicon.

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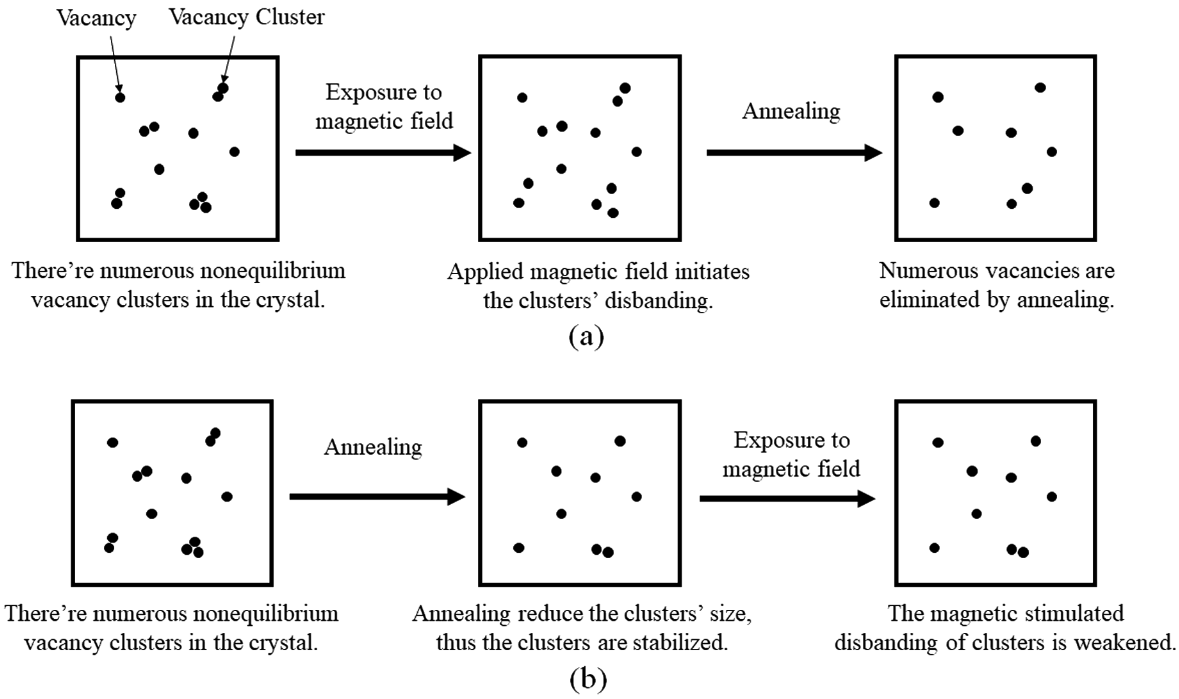

Fig. 1. Changes of the state of vacancy clusters in silicon crystals caused by magnetic treatment and annealing. (a) – Expose the crystals to magnetic field and then anneal them. (b) – Anneal the crystals and then expose them to magnetic field

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