Functional Materials 14, No.2 (2007)

Silicon crystal strength reduction due to magnetoresonance

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Received September 7, 2006

The magnetoresonance influence as well as the microwave superhigh-frequency (SHF) magnetic field effect on the microhardness of silicon crystals has been studied. It is established that the action of SHF field results in decreasing microhardness, which does not relax for initial value during a long time (-50 days). A mechanism has been suggested for the revealed effects.

Изучалось магниторезонансное влияние, а также действие микроволнового сверхвысокочастотного магнитного поля на микротвердость кристаллов кремния. Установлено, что действие сверхвысокочастотного поля вызывает снижение величины микротвердости, которая не релаксирует к исходному значению в течение длительного времени (~50 суток). Предложен механизм выявленных эффектов.

From the viewpoint of modern theoretical models, it is reasonable to consider the mechanism of magnetic field effect on the set of mechanical, electrophysical, and physicochemical properties of a solid body making use of the spin exclusion release rather than of energy effect concepts. That process can be treated basing on the spin chemistry concepts, by analogy with the spin-dependent chemical interactions [1]. However, in this case, it is reasonable to consider the spin-dependent reactions in the defect-paramagnetic impurity system instead of the molecular interactions. To analyze the numerous experimental data obtained when studying both the magnetoplastic effects (MPE) (that manifest themselves as changes in dislocation dynamic behavior in a magnetic field) and magneto-mechanical effects (MME) (that are indicated by the crystal microhardness variations due to magnetic action) [2–6], criteria are necessary which would confirm or deny the spin-associated origin of any magneto-sensitive effect. To prove rigorously the influence of the defect spins on microplastic and micromechanical properties of silicon crystals that were observed in our works [2–4], in our opinion, it was necessary to provide conditions for selective influence on the spin states in pairs of paramagnetic particles that constitute the point defect complexes (PDC). Such a possibility is provided by a microwave or superhigh-frequency magnetic field (SHF) B_1 that is capable of change the multiplicity in the defect pair if it is applied perpendicularly to the constant magnetic field (MF) B_0 but cannot affect the spin orientation if the SHF field is parallel the induction vector of the constant MF ($B_1 \| B_0$). Similar experimental proofs were obtained in studies on the resonance effect on the microhardness and dislocation path in alkali halide crystals and silicon ones [5–8]. So the study of MF influence on micromechanical properties of ionic crystals was resulted in the revealing of crystal plasticization due to excitation of electron paramagnetic resonance (EPR) in structure defects under crossed constant and SHF magnetic fields [5, 6]. Later, the resonance influence of the constant MF and variable SHF crossed therewith on dislocation paths in silicon single crystals was revealed [7] that resulted in the crystal strengthening. The variable magnetic field frequencies causing the maximum changes of the crystal strength and plasticity observed in [5–8] correspond to the resonance frequencies of transitions between the Zeeman sublevels in paramagnetic complexes of point defects or in complexes consisting of a point defect and a dislocation. The dislocation path measurements in NaCl and Si crystals [5–8] make it possible to record the radio-frequency spectrum of electron transitions in the structure defect subsystem. Thus, the EPR that stimulates changes in the crystal microplastic and micromechanical characteristics allows to assume that the primary elementary processes of magnetoplastic and magneto-mechanical effects observed in [2–4] are spin-dependent processes in the crystals. This work is aimed at verification of suggestions concerning the spin nature of MME.

The purpose of the work was to study the microhardness variation of Si single crystals following the simultaneous exposure to crossed constant and microwave magnetic fields at the relationship between the SHF frequency ν and the constant MF induction B_0 meeting the EPR condition $g\mu_B B_0 = h\nu$ where μ_B is Bohr magneton; h, Planck constant; $g \sim 2$, g-factor. Thus, the experimental scheme was similar to the traditional conditions of EPR signal observation, that is, similar to the standard procedure of EPR spectrum measurement except for the microhardness rather than the SHF power absorbed in the sample was used as the resonance response.

Silicon samples grown by Czochralski technique under phosphorus or boron doping were used. The samples were placed into a resonator that was coherent with a magnetron at the constant frequency $\nu = 9.425$ GHz and positioned between electromagnet poles. The magnetoresonance effects were studied using a standard X range radiospectrometer SE/X-2544 "Radiopan" at the modulation frequency 100 kHz and the sweep range of the constant MF B_0 0.04 to 7 kOe. The samples were exposed in crossed constant (at B_0 induction value) and variable SHF (at B_1 induction value) fields for 6 min, the B_0 and B_1 vectors were perpendicular to one another. Then the samples were extracted from the resonator and the microhardness was measured using a PMT-3 hardness tester. The microhardness measurements were carried out for reference samples not treated in MF. The microhardness measurement error was about 4 %. We have observed a microhardness reduction in Si crystals exposed to resonance conditions. That reduction can be classified as a peculiar magneto-mechanical effect.

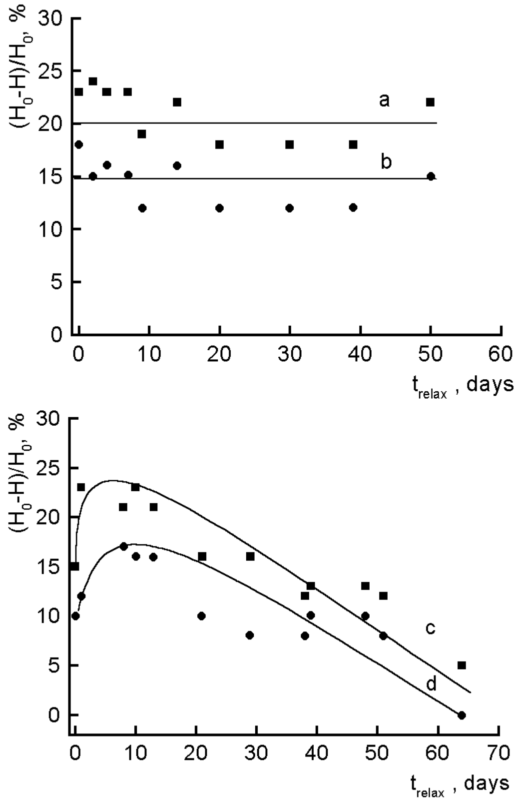

Fig. 1. MME relaxation in Si samples after magnetoresonance influence (a) and after action of microwave UHF magnetic field (b): H_0 is the microhardness of the initial (reference) Si samples; H is the microhardness of Si samples subjected to magnetoresonance influence or the action of microwave UHF magnetic field; *1*,*3* - n-Si crystals; *2*,*4* - p-Si crystals.

We have found that the MME amounts about 20 % in n-type Si crystals (phosphorus doped) and about 15 % in p-type (boron doped) ones (Figs. 1a and 1b, respectively). Thus, a magneto-mechanical effect has been revealed consisting in the strength reduction of Si crystals due to magnetoresonance in crossed constant and SHF magnetic fields. It is seen in Figs. 1a and 1b that the EPR-excited MME does not relax during a long time (about 50 days). It has been pointed in [5–8] that under conditions meeting the resonance criteria, the mutual orientation of the particle spins varies; this orientation defines the interaction possibility due to Pauli's prohibition. In our specific case, it can be assumed the matter that the matter is of the spin interaction and spin orientation change of defects forming a point defect complex. The resonance excitation in structure defects in crossed magnetic fields may give rise to spin singlet-triplet transitions in PDCs, for example, in SiO_x precipitate complexes. Such spin-dependent reactions in PDCs may result in decomposition thereof. The defect structure modified due to magnetic influence causes changes in the structure-sensitive properties, for example, in microhardness. Thus, the EPR excitation in the defect subsystem may be a way to influence the behavior of that subsystem and the processes defined by the latter [5–8].

To conclude, it is to note that the effect of the microwave SHF field only resulted also in the microhardness variations in silicon crystals (Fig. 1c, d). It is of interest that after the SHF field exposure is over, the MME caused by that exposure varies non-monotonously and does not relax for a long time (about 50 days), similar to the EPR-induced MME. According to literature data [1, 7], the SHF field induces the singlet-triplet (S-T) conversion in singlet pairs formed by the defects. Basing on [7], it can be assumed that in the presence of a constant MF, the SHF field amplifies indirectly the S-T transition intensity. As noted above, the intersystem crossing in PDCs causes the breakdown of chemical bonds in the corresponding complexes (for example, in SiO_x precipitates) and sets conditions for their subsequent modification. The running of the spin-dependent processes mentioned results in formation of a "new" modified structure and gives rise to the MME. Our results prove that the structure relaxation of magneto-sensitive complexes causing the MME in silicon crystals is a spin-dependent process.

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Магніторезонансне знеміцнення кристалів кремнію

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Вивчено магніторезонансний вплив і дію мікрохвильового надвисокочастотного магнітного поля на мікротвердість кристалів кремнію. Встановлено, що дія надвисокочастотного поля викликає зменшення мікротвердості, яка не релаксує до вихідного значення протягом тривалого часу (~50 діб). Запропоновано механізм виявлених фізичних ефектів.