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Thermodynamic model of helium and hydrogen co-implanted silicon surface layer splitting

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ABSTRACT

A thermodynamic model of the evolution of microcracks in silicon caused by helium and hydrogen co-implantation during annealing was studied. The crack growth rate relies on the amount of helium atoms and hydrogen molecules present. Here, the crack radius was studied as a function of annealing time and temperature, and compared with experimental results. The mean crack radius was found to be proportional to the annealing temperature and the helium and hydrogen implanted fluence. The gas desorption should be considered during annealing process.

1. Introduction

Hydrogen and helium ion co-implantation in silicon can effectively fabricate silicon-in-insulator (SOI) wafers, called the Smart-cut process [1,2]. Due to hydrogen being more efficient in interacting chemically with the implantation damage and creating H-stabilized microcracks. He can induce a high pressure in the microcracks [3]. It has been reported that fluences of $1 \times 10^{16} He^+/cm^2 + 0.75 \times 10^{16} H^+/cm^2$ can effectively induce layer splitting, while a fluence of $5 \times 10^{16} H^+/cm^2$ is needed for H implantation alone [4]. Therefore, it greatly decreases the H fluence needed for layer splitting. There are many studies on the thermal evolution of the Smart-cut process as the function of fluence, annealing temperature, annealing time, and order of implantation [5,6]. It has been shown that the mechanism of the growth of microcracks is related to the amount of trapped atomic and molecular hydrogen and trapped helium in the microcracks. A high pressure in the microcracks can lead to the growth of the microcracks into microvoids and an eventual intersection of the microvoids to form two continuous internal surfaces. The time required to form hydrogen-induced splitting after bonding is about ten times longer than the time required to form hydrogen-induced surface blisters in unbonded samples, while the activation energies of the two processes are the same [7]. Han and Yu [8] reported a model to estimate the hydrogen-implantation for the growth of hydrogen-blisters and wafer splitting with the fluence, annealing time and temperature. Here, we establish the thermodynamic model of the Smart-cut process with the consideration of the growth of the microcracks in He and H co-implanted silicon, and compared the model with the experimental results.

2. Experiment

The present data of Czochralski grown, *n*-type, 0.01–0.09 Ω cm (1 0 0) Si wafers, implanted with an energy of 30 keV He to a fluence of $3 \times 10^{16} He^+/cm^2$ at 600 K followed by an energy of 24 keV H to a fluence of $2 \times 10^{16} H^+/cm^2$ at room temperature was used. In the experiment, the current densities of He and H were 0.8 and 0.5 $\mu A/cm^2$, respectively. These energies were chosen according to TRIM calculations in order to guarantee maximum implantation profile overlap [9]. The samples were annealed in a flux of N_2 atmosphere at temperatures ranging from 623 and 1073 K for 30 min, or a time ranging from 5 to 60 min at 773 K. In order to precisely control the annealing process, the furnace temperature was preset before the samples were put in and the samples were taken out of the furnace quickly after finishing annealing. The surface morphologies, such as blisters or craters, appeared after appropriate annealing. Such features were detected by using an optical microscope and atomic force microscope (AFM).

3. Results and discussion

He implantation can introduce a lot of vacancies and interstitials. During successive H implantation, the H ions may chemically interact with broken silicon bonds to form hydrogenated complexes, Si–H. During annealing, He atoms can diffuse into vacancies and the activation energy of this process is about 0.96 eV [10]. In

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addition, some trapped hydrogen atoms dissociate from Si–H complexes and then diffuse into vacancies to form hydrogen molecules. Due to vacancies containing a lot of helium atoms and hydrogen molecules, vacancies will grow up with annealing and finally form microcracks observable by transmission electron microscopy. Sufficient pressure is exerted on the inner walls of microcracks, leading to microcracks anisotropically growing and overlapping when the pressure at the microcrack edges exceeds the fracture limit of silicon. According to fracture mechanics [8,11], we treat the helium and hydrogen-induced subsurface microcrack as a penny-shaped, as shown in Fig. 1. The microcrack edge is taken to be circular of radius a and the opening displacement profile of the microcrack face is

$$u_z(z = \pm 0, r) = \pm a \frac{4p(1-\nu^2)}{E\pi}\sqrt{1 - r^2/a^2}, \tag{1}$$

where a is the radius of a microcrack, p is their internal pressure, ν is the Poisson ratio and E is Young's modulus. When the internal pressure p is not smaller than the fracture limit of silicon, the volume of the blister will expand for the helium and hydrogen agglomeration. Therefore, we speculate that the internal pressure p keeps a constant that equals the fracture limit of Si wafer. By integrating Eq. (1) over the total crack area, the volume of the crack is

$$v(a) = \frac{16}{3}(1-\nu^2)a^3 p/E. \tag{2}$$

The growth of a microcrack is controlled by the stress applied to the surface of the microcrack. Helium atoms can easily diffuse into microcracks with an activation energy E_{He} of 0.96 eV. A trapped hydrogen atom dissociates from a hydrogen complex Si–H with an activation energy E_a of 1.8 eV, and diffuses with an energy E_d of 0.48 eV into microcracks. If the helium fluence is Φ_{He} and hydrogen-implantation fluence is Φ_H before annealing, the released helium fluence is $\Delta\Phi_{He}$ under annealing, then the rate of He agglomeration in the implanted region is

$$\frac{\partial \Delta\Phi_{He}}{\partial t} = -k_1 \Delta\Phi_{He}, \tag{3}$$

where k_1 is the reaction rate constant expressed as

$$k_1 = \frac{1}{\tau}\exp\left(-\frac{E_{He}}{k_B T}\right), \tag{4}$$

where T is the annealing temperature, k_B is Boltzmann constant and $1/\tau$ is the helium vibration frequency in an interstitial site about $2 \times 10^{13}\ s^{-1}$. The release hydrogen fluence is $\Delta\Phi_H$ under annealing, and then the rate of hydrogen generation from the implanted region is

$$\frac{\partial \Delta\Phi_H}{\partial t} = -k_2 \Delta\Phi_H, \tag{5}$$

and the reaction rate constant is

$$k_2 = \frac{1}{\tau}\exp\left(-\frac{E_a + E_d}{k_B T}\right), \tag{6}$$

where τ is the phenomenological parameter about 10^{-12} s relating to the stretching frequency of the dissociating Si–H bond. Let

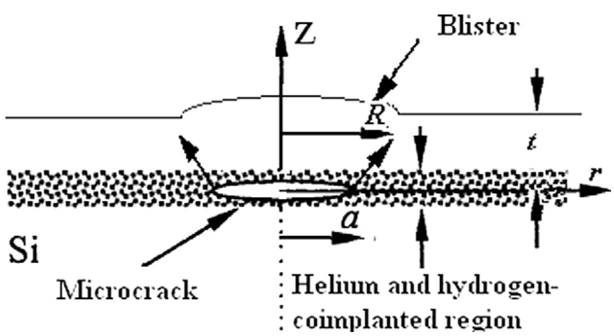

Fig. 1. Schematic of the formation of a microcrack with the radius a locates in a helium and hydrogen-co-implanted silicon wafer. Meanwhile, a blister of radius R is suspended over the microcrack. The depth of the microcrack is t.

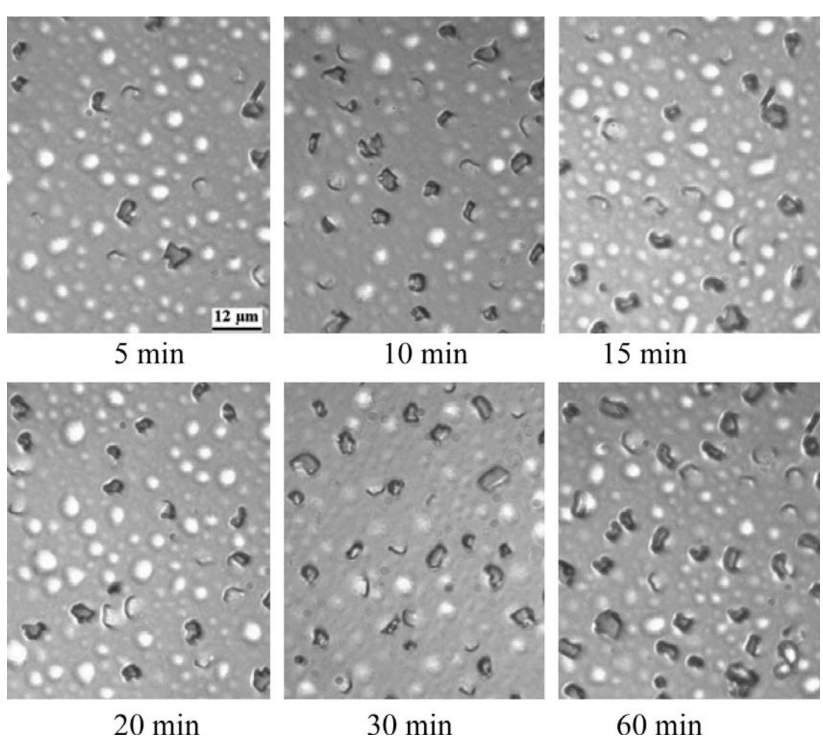

Fig. 2. Optical microscopic surface images of the helium and hydrogen co-implanted sample after thermal annealing at 773 K with different time.