Control of Surface Roughness of Si and Ge Single Crystal by Laser Radiation

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Analysis of reordering of Ge amorphous surface by ruby laser; kinetics of the surface annealing after ion implantation using the optical reflectivity; occurrence of laser induced periodical structures; nanohills formation by Nd:YAG laser allowed us to resume common features for these process which belong to Thermogradient effect. Experimental data on annealing of p-Si (111) and i-Ge (111) mechanically polished surfaces by Nd:YAG laser radiation using of optical microscopes and atomic force microscopes, optical reflectivity of He-Ne laser and the four-probe method confirmed the main role of Thermogradient effect in the reordering process of the mechanically polished surface of Si and Ge to single crystal. It was found that row of nanohills arises on the irradiated surface of Ge and Si single crystal after irradiation by Nd:YAG. Photoluminescence of nanohills row in visible range of spectra was established. The photoluminescence of Ge and Si samples after irradiation by Nd:YAG laser is explained with quantum confinement effect on the top of nanohills – quasi quantum dots. For explanation of this effect gathering of interstitial atoms at the irradiated surface is proposed.

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1. Introduction

The possibility to achieve a reordering of amorphous semiconductors even by irradiating the samples with superimposed laser pulses so as to operate below the melting regime was shown [1,2]. The process has been shown to occur gradually due to the low-power ruby laser annealing of ion-implanted Ge [3] with several successive superimposed laser pulses (pulse duration τ=30 ns; wavelength λ= 694.3 nm; intensity I =1.2 - 2.8 MW/cm^2). The corresponding temperature reached was in the 180 – 450 C range. It was concluded that enhancing of crystallization process takes place due to thermal gradient.

An opposite conclusion was made in paper [4]. As a result of kinetics study of annealing amorphous Ge by ruby laser using the optical reflectivity at λ = 1.06 μm, it was concluded that melting process takes place. It was shown that intensity of laser radiation (LR) needed for melting of amorphous material is 4 times lower than that for crystalline one. The smoothing process of the mechanically polished surfaces of compound semiconductors such as InSb and CdTe [5] is observed using Nd:YAG lasers.

Analysis of surface modification processes such as: defects annealing after ion implantation and reordering of amorphous layer; smoothing of mechanically polished damaged surface of semiconductor; occurrence laser induced periodical structures (LIPS) on semiconductors and metals [6], nanohills formation on Ge surface allowed us to resume common features for these processes: 1) gradual character – pulse by pulse effects become more expressive; 2) the threshold character of the effects – there is a minimum intensity, the so-called threshold intensity (I_{th}) of LR, which causes surface modification; 3) processes take place in a matter in solid state; 4) the presence of temperature gradient. The following features belong to thermogradient effect (TGE) [5], too. TGE is the drift of point defects: impurity atoms and intrinsic defects of crystalline lattice (vacancies and interstitials) in the field of temperature gradient.

Therefore the aim of our investigation is to study the role of TGE on crystallization process of the mechanically polished surface and to determine origin of photoluminescence (PL) of the nanohills formed by laser radiation of Si and Ge under exposure to powerful laser radiation.

2. Experiments and Discussion

Experiments were performed in ambient atmosphere at pressure of 1 atm. T = 20^o C, and 60% humidity. Radiation from Nd:YAG laser (pulses duration τ=15ns ; basic wavelength λ = 1.06 μm or second harmonic wavelength λ_2 = 532nm; pulse rate 12.5 Hz; power P = 1MW) was directed normally to the surface of i-type single crystal Ge (111) with dimensions 1.0 × 0.5 × 0.5cm^3 and resistivity ρ = 45 Ω cm or of p-type Si(B) of the surface (111) wafer with ρ = 10 Ω cm.

The samples were polished mechanically by diamond powder with a grain diameter of 1μm on all the surfaces. Diameter of the laser beam was 3 mm. Irradiation was carried out with superimposed laser pulses in the same spot of the surface (I regime) or in scanning manner with step of 1μm (II regime). Surface resistance of samples was measured before and after irradiation by the four-probe method. The surface morphology was studied using optical microscope and atomic force microscope (AFM). Reflection coefficient (R) was measured using He-Ne laser at λ =633 nm. It was found that irradiation of Ge sample by second harmonic of Nd:YAG laser with intensity of LR I = 1.6 MW/cm^2 in I regime after irradiation by 10 pulses causes decrease of R (see Fig.1). In the beginning, the diameter of black spot on the surface was approximately 1 mm. It is increased pulse by pulse until 3 mm after 100 pulses as shown in Fig.2 in the same time R decreased by 10%. But after irradiation of the surface by only one pulse, no change of the surface morphology and R was observed. Study of dynamics of annealing mechanically polished surface of p-Si by second harmonic of Nd:YAG laser in II regime showed the possibility to smoothen it.

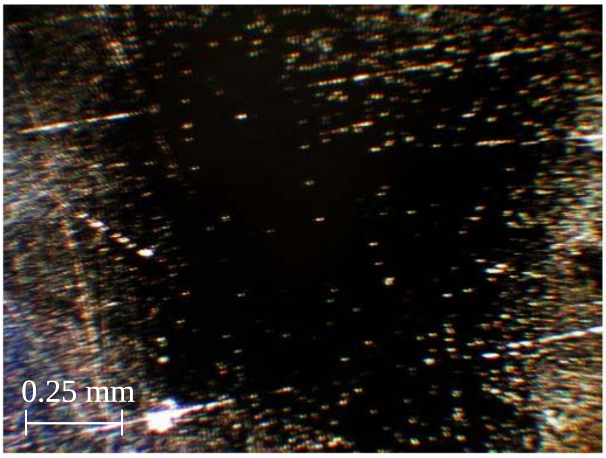

Fig.1. Optical image of Ge surface after irradiation by Nd:YAG laser second harmonic at intensity I = 1.6 MW/cm^2 after 10 superimposed pulses.

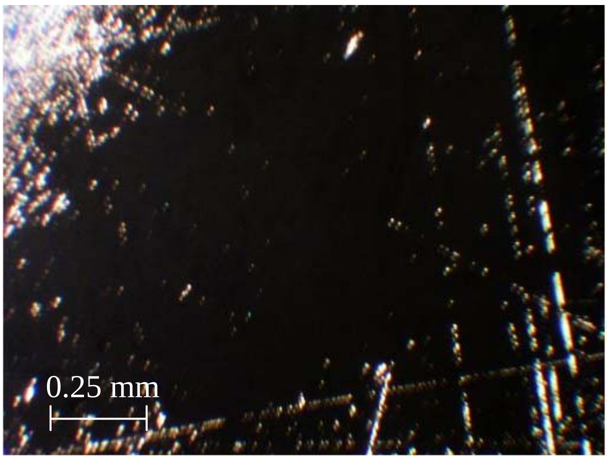

Fig.2. Optical image of Ge surface after irradiation by Nd:YAG laser second harmonic at intensity I = 1.6 MW/cm^2 after 100 superimposed pulses.

AFM 2D images of Si (111) surface and section analysis are show in Fig.3. and Fig.4. before irradiation by laser Fig. 3. and after irradiation Fig.4. First of all we can see smoothening up of the irradiated surface after irradiation by laser at I = 0.7 MW/cm^2. Roughness of the surface decreases 4 times after irradiation by laser.

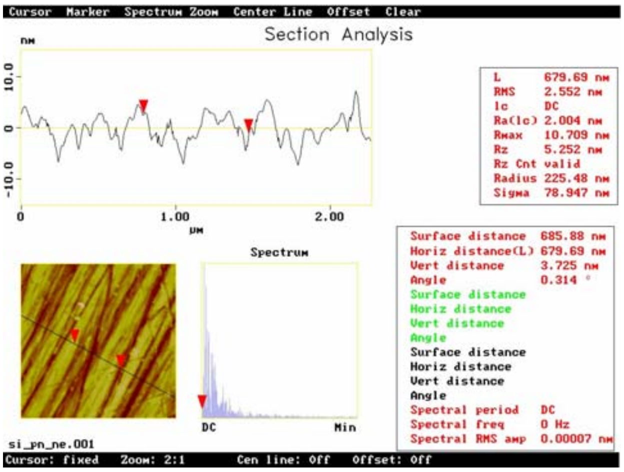

Fig. 3. AFM 2D images of Si (111) surface and section analysis initial after mechanical polished.

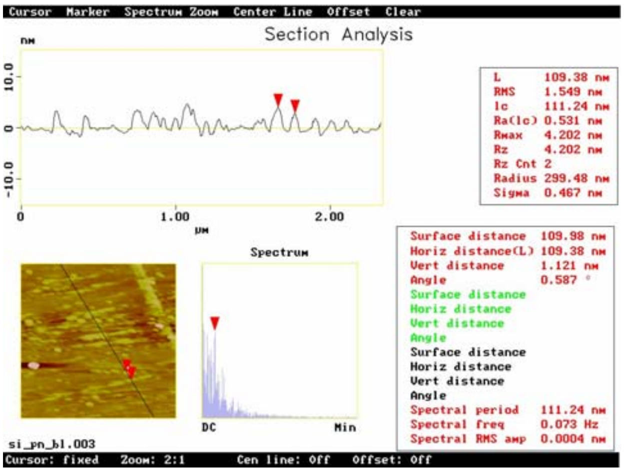

Fig. 4. AFM 2D images of Si (111) surface and section analysis irradiated by Nd:YAG laser second harmonic at intensity I = 0.7 MW/cm^2.

Moreover new nanostructures arise on the smooth surface, which grow with intensity of LR and number of pulses. These rows of nanostructures have parallel location; their dimensions are the following: length ≈1μm; height ≈5 nm; width ≈50 nm which can see in Fig. 3., 4. and 5. The resistance of the irradiated surface of Si wafer is increased by 10^4 times comparison with the mechanically damaged surface.

For explanation of these results we supposed presence of TGE because irradiation of the samples takes place by highly absorbed LR, which causes high gradient of temperature. Temperature of the irradiated surface is lower than melting temperature. Under exposure of LR oxygen [5] and interstitial atoms drift pulse by pulse to the irradiated surface of Si sample as show in Fig. 6. As a result concentration of interstitial atoms increase and it leads to decrease of melting temperature. Decrease of T_m leads to movement of interface solid state – liquid in the depth of sample as show in Fig. 7. When the interface reach to single crystal part of sample recrystallization of damaged layer so called laser epitaxy takes place.
The effect gathering of the interstitial atoms at the irradiated surface leads to creation of nanostructures on the surface similarly to stacking faults structures created on Si wafer by oxidation [7].

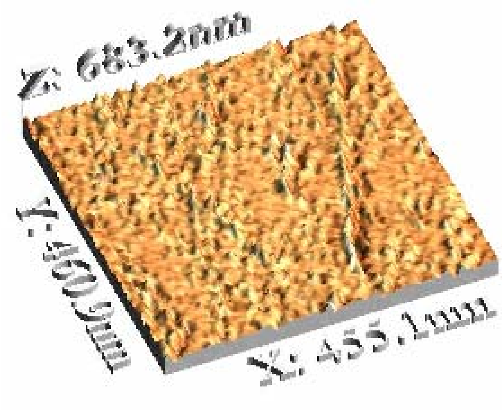

Fig.5. AFM 3D image of p-Si(111) surface after irradiation by Nd:YAG laser at I=1.0MW/cm^2.

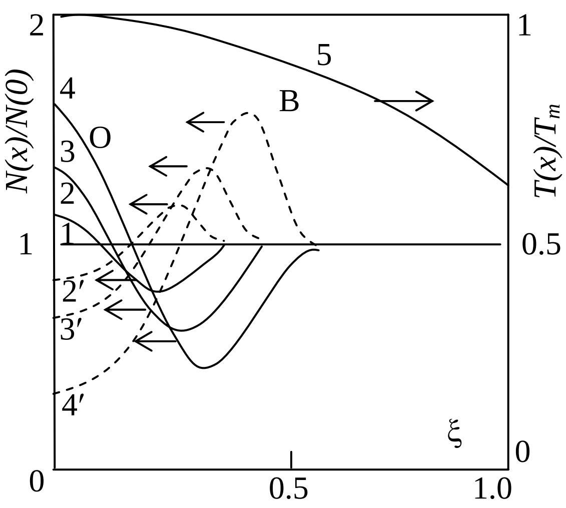

Fig. 6. Kinetics of distribution of O and B atoms in grad T. Curves 2,3,4 for O atoms; curves 2', 3', 4' for B atoms and curve 5 – temperature field, where x is the coordinate directed from the surface to the bulk of a semiconductor; xo is the characteristic width of the temperature distribution; N is concentration of the impurity atoms; ξ = x/xo [5].

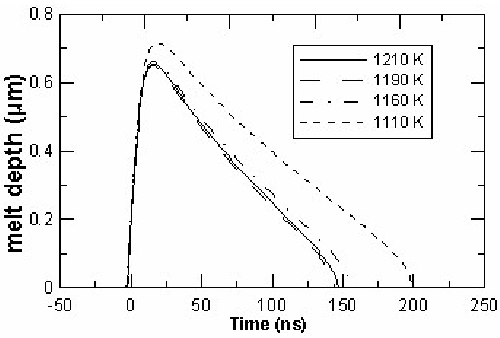

Fig.7. Kinetics of interface solid state-liquid movement at different melting temperature.

Analyzing the interaction of highly absorbed laser radiation (LR) pulses of different intensity and pulse duration with surfaces of Si [1] and Ge [2] allowed us to conclude that the main role in amorphisation-crystallization process of semiconductor belongs to Thermogradient effect (TGE) – drift of point defects (impurities and intrinsic defects of crystalline lattice) in the field of temperature gradient. Thus, modification of Si surface under exposure to LR of Nd:YAG laser occurs during 1000-3000 pulses if pulse duration is within a picoseconds range [4], during 50-100 pulses of nanoseconds range and during one pulse of milliseconds range as our experiments have shown. The LR threshold intensity reduces correspondingly from GW/cm^2 down to KW/cm^2. The effect of saturation was observed at a constant intensity both in our experiments on smoothening of Si and Ge surface and in publication [4].
It may be concluded that in the temperature (T) gradient field point defects drift from bulk to the irradiated surface of a semiconductor, but the distance of drift depends on duration of a laser pulse. The calculated distribution of O and B atoms in Si [2], depending on number of laser pulses, have shown that concentration of O atoms rises from pulse to pulse at the irradiated surface. The effect of saturation of impurity atoms is determined by equilibrium of the drift and diffusion flows of defects.
Surface smoothening of single crystals Si and Ge after mechanical treatment cannot be explained by melting of the surface layer at the constant melting temperature. Thus, our experiments have shown that this process can occur at lower intensities of LR than those resulting in melting of the crystal lattice. However, irradiation with LR of lower intensity requires a larger number of laser pulses for smoothening of the surface, and this dependence is inversely proportional. According to concepts of physical chemistry, a rise of impurity or intrinsic defect concentration causes decrease of the melting temperature of a crystal. It explains the effect of surface smoothening at LR of low intensities and multiple irradiation of a semiconductor. This process is characterized by graduate changes of electrical, optical and structural properties of semiconductors from pulse to pulse. Decrease of reflection coefficient (R) on 10% of

the irradiated surface we have observed in visible range of spectrum.

Thus, the main peculiarities of phase transition on a semiconductor surface may be explained by TGE. An interesting phenomenon was observed on the surface of Si after irradiation by Nd:YAG laser at intensity I= 9.0 MW/cm^2, whish is lower than needed for smoothing this surface I= 14.0 MW/cm^2. There is roughness up 4 times of the irradiated surface. Moreover, on the smooth surface nanohills rows arise and grow with number of laser pulses. These rows of nanohills have parallel location; their dimensions are the following: length ~ 1μm; height ~5 nm; width ~50 nm. This effect we explain by gathering of the interstitial atoms at the irradiated surface which leads to creation of nanostructures on the surface similarly to stacking faults structures created on Si wafer by oxidation [5].

In the PL spectrum of irradiated Si crystal (Fig.8) we have observed band gap luminescence consisting of two components 740 nm (1.68 eV) and 890 nm (1.39 eV). Calculation size of Si quantum dots [8] from PL band gap shift using the maximums of PL bands at 1.68 eV and 1.39 eV, gave diameters of quantum dots 6.7 nm and 9.5 nm at parameters of Si: m_e=0.26 m_o and m_h=0.49 m_o for electron and hole effective masses, respectively.

These value correlates well with other authors experimentally observed dates, for example [9].

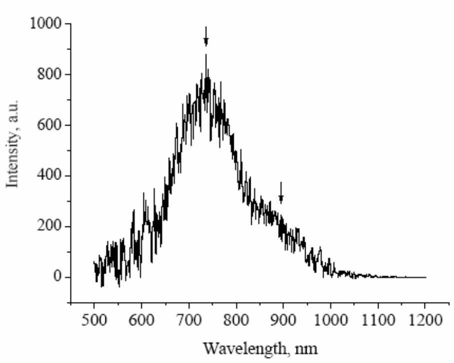

Fig.8. PL spectrum of the irradiated surface by Nd:YAG laser of Si crystal.

3. Conclusion

At the first stage of a reordering of the mechanically polished surface of Si and Ge single crystal by Nd:YAG laser second harmonic Thermogradient effect has a main role. Row of nanohills arises on the irradiated surface of Si due to gathering of interstitial atoms on the surface after its reordering. Photoluminescence of Si after laser radiation in visible range of spectra was established.

References

[1] G. Vitaly: Phys. Lett. 78 A (1980), 387.

[2] G. Vitali, M. Marinelli, U. Zammit and F. Scudieri: Phys. Lett. 94A, (1983), 320.

[3] G. Vitali, M. Marinelli, U. Zammit and F. Scudieri: Appl. Phys. A 35 (1984), 233.

[4] G.G. Zakirov, G.D. Ivlev, I.B. Khaibullin: Fhys and Tech. of Sem., 22, (1988), 947 (in Russian).

[5] A. Medvid': Defects and Diffusion: 210-212 (2002), 89.

[6] F. Jeff, I.E. Sipe, van Orief: Phys. Rev. B, 30 (1984), 2001.

[7] D. Kropman, T. Kerner, O. Abro, U. Graste: Mat. Sci. and Eng. B, 114-115 (2004), 295.

[8] Al.L.Efros and A.L.Efros, Phys. and Tech. of Semicond. 16 (1982) 1209.

[9] C. Barthou, P.H Duong, A. Oliver, J.C.Cheang-Wong, L. Rodriguez-Fernandez, A Crespo-Sosa, T. Itoh, P.Lavallard: J. Appl. Phys., 93 (2003) 10110.

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