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INFRARED INTERBAND ABSORPTION IN SILICON HYPERDOPED WITH SELENIUM BY ION IMPLANTATION WITH SUBSEQUENT PULSED LASER ANNEALING

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Слои кремния, сверхпересыщенные селеном, были сформированы путем имплантации Se (140 кэВ, 3.1×10^{15} см$^{-2}$ и 6.1×10^{15} см$^{-2}$) с последующим импульсным лазерным отжигом (λ = 694 нм, W = 2.0 Дж/см^2, τ=70 нс).Концентрацию атомов Se определяли с помощью резерфордовского обратного рассеяния. Образование промежуточной зоны внутри запрещенной зоны Si было доказано с помощью сканирующей туннельной спектроскопии. Для оценки степени кристалличности слоя легированного кремния и определения доли атомов Se в узлах решетки Si использовались значения выхода обратного рассеяния χSi и χSe, полученные из спектров RBS в режиме каналирования. Сравниваются и обсуждаются характеристики экспериментально зарегистрированных и теоретически оцененных характеристик промежуточной зоны. Наблюдалось значительное увеличение поглощения света в широкой области спектра (0.2-23.0 мкм).

Silicon represents the fundamental material of microelectronics. However, it was used in optoelectronics much less frequently because it has a relatively large band gap (1.12 eV) and is not able to absorb electromagnetic radiation of wavelength longer than 1.1 μm. As a result, silicon photodetectors are insensitive at three main fiber-optic communication wavelength bands: S (1460-1530 nm), C (1530-1565 nm) and L (1565-1625 nm) [1]. Extending the sensitivity of silicon- based and silicon technology- compatible photodetectors to the IR range is therefore an active area of research. Currently, it is established that single-crystal silicon oversaturated with chalcogen atoms (S, Se and Te) exhibits the highest absorption coefficient ($\sim10^4$ cm^{-1}) of light in the IR spectral range at room temperature [2-4]. The present work is devoted to Se-hyperdoped silicon layers fabricated by ion implantation followed by pulsed laser annealing. Our investigation focuses on the effect of ion fluence on structural and optical properties of Se-supersaturated silicon layers as well as on the theoretical and experimental evaluation of intermediate band characteristics.

Silicon (111) p-type double side polished wafer was implanted with 140 keV Se$^+$ ions to the fluence of 3.1×10^{15} (Se (0.75%)/Si) and 6.1×10^{15} (Se (1.5%)/Si) ions/cm^2. Pulsed laser irradiation of the implanted samples was carried out under the experimental conditions, i.e., with optical and pyrometric diagnostics in situ of phase transformations initiated by a ruby laser pulse (λ = 694 nm, FWHM = 70 ns) with a uniform pulse energy distribution along the area with a diameter of 4 mm. The energy density W in the laser pulse was set as 2 J/cm^2. Scanning tunnelling microscopy (STM) and spectroscopy (STS) measurements were conducted using a commercial low-temperature system from the Createc with a base pressure of 3×10^{-11} mbar at liquid nitrogen temperature (77 K). The preparation chamber of the ultrahigh-vacuum system is fitted with a cooling/heating stage (LEED). STM data were obtained in constant current mode using the single-crystalline W (001) tip. The samples were sputtered by Ar ions at the energy of 750 eV under 2×10^{-5} mbar ambient for 10 min in the preparation chamber. To collect some statistics and check reliability the STM/STS measurements were carried out at 5 different places with different scan windows.

Results and discussion

The RBS spectra in the random and channeling regimes were obtained for selenium – implanted and annealed samples. For the random measurement, the sample were titled by 5°and then rotated. After implantation the amorphous layers are produced for both ion fluencies. For these ion fluences, the random yields of Se in ion-implanted and laser-annealed samples are almost the same. This suggests that Se is almost not lost during the laser annealing. The corresponding measured concentration profiles and calculated by SIMNRA code[5], for the as-implanted and laser-treated samples are presented in Fig.1. The Si melt lifetime τ_m and thickness d_m of melted layer formed by ruby laser pulse with the energy density $W = 2J/cm^2$ amounts to 0.27 μs and 0.4 μm, respectively.

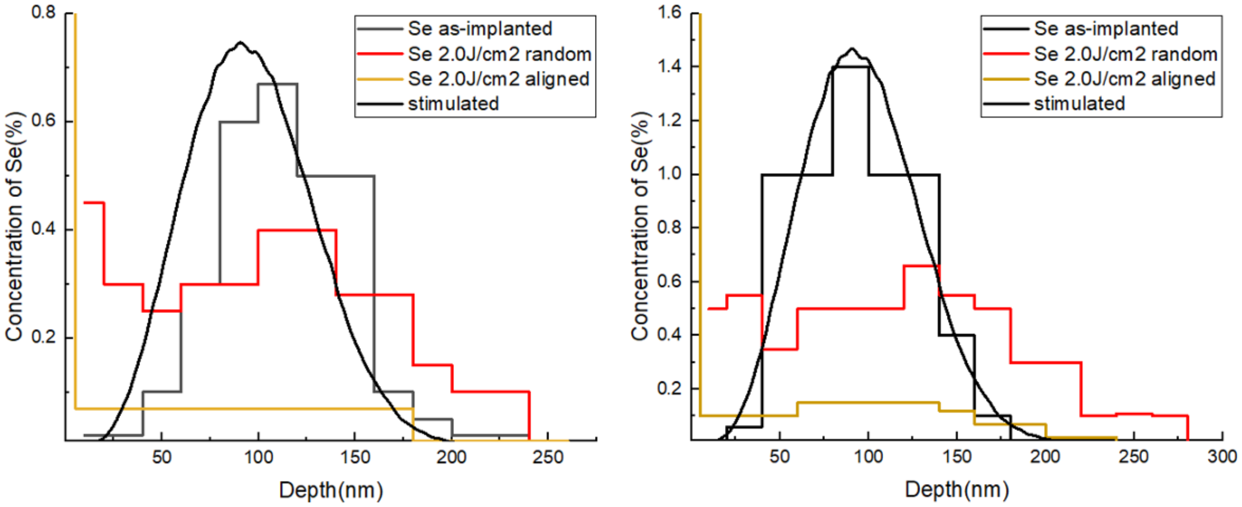

Figure 1 – Depth distribution of Se concentration measured in random and channeling regimes on the samples implanted with the fluence of 3.1×10^{15} cm^{-2} (a) and 6.1×10^{15} cm^{-2} (b).

Table 1 – The degree of crystallinity of silicon layer (f_{cr}) and fraction of impurity at lattice sites after implantation of selenium ions and laser annealing $W= 2\ J/cm^2$

Se ion fluence (cm^{-2})	$f_{cr}=(1-\chi^{Si})/(1-\chi^{min})$,%	Se yield in random case (Se/cm^2)	Se yield in aligned case (Se/cm^2)	Se fraction in the lattice sites
$3.1\cdot10^{15}$	93.6	$3.05\cdot10^{15}$	$0.86\cdot10^{15}$	72.0%
$6.1\cdot10^{15}$	91.9	$5.46\cdot10^{15}$	$1.66\cdot10^{15}$	69.6%

STS data (not presented) show the visualization of band structure spatial fluctuations by the STS analysis and surface topography by the STM examination. The STS data reveal the sub-band states from 0.48 to 0.6 eV above the Fermi level. The average position for 5 pairs of measurements at different points (x,y) of the sample is 0.55 eV. The width of inter-band is varying from 0.15 eV to 0.3 eV. Roughly 1 % of spectra have the in gap-feature.

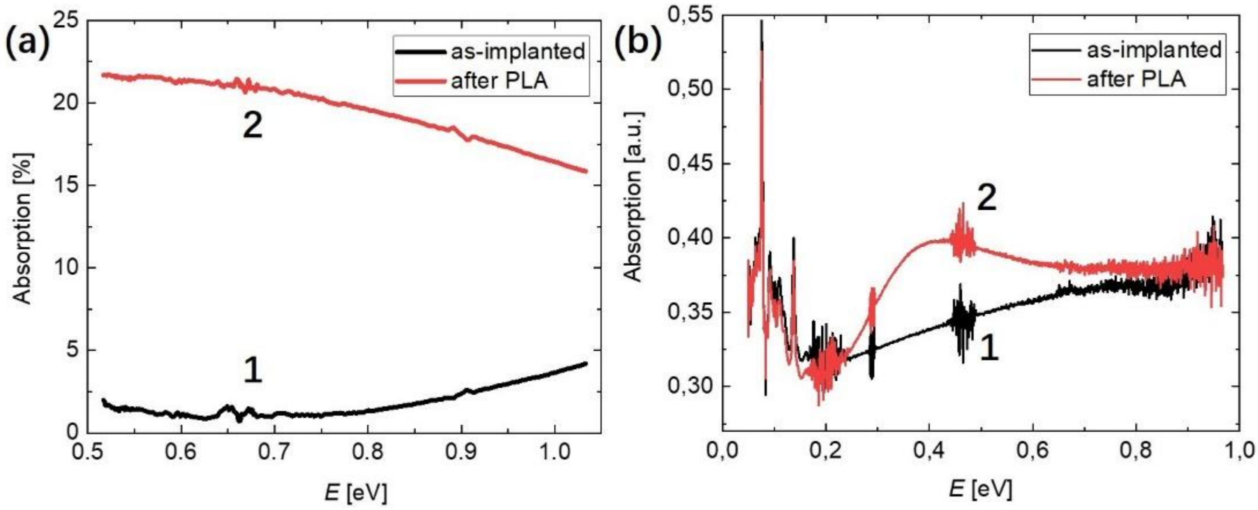

Figure 2 – Absorption spectra in NIR (*a*) and MIR (from FTIR spectra) (*b*) spectral ranges of the Se-implanted sample (Se (0.75%)/Si) before and after PLA

Figure 2 shows absorption spectra in NIR and MIR spectral ranges. The presented data (Figure 2b) for MIR also show increase of absorption after PLA. Moreover, there is observed the absorption band with maximum at 0.4 eV and with FWHM of 0.25 eV.

Conclusion

The energy density of W= 2J /cm^2 is optimal from the point of view of structural perfection (>91%) of silicon and maximum concentration of Se at lattice sites (>69%) of silicon. The STS data reveal the sub-band states from 0.48 to 0.6 eV above the Fermi level inside the Si band gap. The measured characteristics of the intermediate band are in a reasonable agreement with the theoretical data of Ref[6].The formation of intermediate sub-band inside Si band gap by hyperdoplng with selenium and subsequent pulsed laser annealing lead to an increase in the intensity of the absorption spectrum by about 17 times in NIR range.

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