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Absolute Photon Yield from Silicon Surface under Electron and Ion Irradiation

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Abstract—The characteristics of the optical radiation accompanying the bombardment of silicon surface by electrons and medium-energy ions have been studied. The continuous radiation observed in this case is related to interband electronic transitions. The characteristic radiation (which is present in both cases), in the case of ion bombardment, is emitted by silicon atoms sputtered in the excited state and scattered helium ions; in the case of electron bombardment, this radiation is emitted by desorbed excited atoms and residual atmosphere molecules, which cover the silicon surface under study.

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INTRODUCTION

Wide application of silicon in modern micro- and nanotechnologies causes constant interest in investigation of its various characteristics and processes in it, in particular, those occurring under its irradiation with fluxes of particles and photons [1, 2]. On the one hand, search for informative methods for monitoring surface microscopic characteristics continues. On the other hand, experimental data contributing to fundamental knowledge of the complex secondary-emission phenomena are accumulated. The character of light emission from Si (111) surface subjected to external action was analyzed by the methods of ion-photon spectroscopy (IPS) and electron-photon spectroscopy (EPS). Comparative analysis of the possibilities and informativeness of these optical methods in study of the processes on Si (111) surface seems to be interesting for us. Our main purpose was to reveal the distinctive features in the electron-induced photon emission (EIPE) and ion-induced photon emission (IIPE) spectra of silicon and a difference in the absolute photon yield from silicon surface per incident particle.

The electronic structure of silicon surface has been analyzed in many studies. In [3, 4], it was investigated by angular-resolved photoemission. In [3], a peak was found at 0.7 eV, which was related to the excitation of surface electronic states. The investigations performed in [4] revealed features at 0.8 and 1.1 eV in the photoemission spectra, which were assigned to excitation of bulk electronic states.

The energy-loss spectra of pure silicon surfaces and surfaces covered with different adsorbates were studied in [5, 6], where features peaking at about 0.4 and 1.25 eV were revealed. These features were attributed to the interband transitions involving surface electronic states; the features near 1.1 and 0.8 eV were attributed, respectively, to the interband transitions involving bulk electronic states and the transitions from the upper valence band to the vacuum level.

EXPERIMENTAL

The IIPE characteristics of silicon were studied on a Karpaty system [7]. Silicon surface was irradiated with 15-keV He^+ ions at an angle of 30° to the normal to the surface. The current density on the target and the residual gas pressure in the working chamber were, respectively, $J_{\text{ion}} = 2.4$ mA cm^{-2} and $P_{\text{ion}} \leq 3 \times 10^{-4}$ Pa. The emission from the silicon surface irradiated by charged particles was studied in the range from 200 to 600 nm. It was focused by a lens on the entrance slit of an MDR-2 monochromator and then the selected part was detected by a FEU-106 photomultiplier in the photoelectron count mode. The desired signal was measured by a frequency meter, and the emission spectra were recorded using a KSP-4 electronic potentiometer.

EIPE investigations were performed on an ultrahigh-vacuum electron–photon spectrometer [8] developed on the basis of a commercial USU-4 system. The silicon surface was irradiated with a monochromatic 800-eV electron beam at an angle of 25° to the normal to the surface. The residual atmospheric pressure in the working chamber did not exceed 10^{-7} Pa. The electron current density could be changed from zero to 7.6 mA cm^{-2}. The optical emission due to the interaction of electrons with the silicon surface was studied in the range 200–800 nm. An MDR-12 monochromator was used to analyze the emission spectrum. In other details, the technique and method for detecting and recording EIPE spectra were analogous to those described above for IIPE. Since the MDR-12 monochromator, in contrast to MDR-2, uses two diffraction gratings in the wavelength range under study (200–800 nm), the relative sensitivity curve was measured for both gratings, in ranges 200–500 and 400–1000 nm (gratings 1 and 2, respectively).

The recording systems in both experimental setups were calibrated using reference sources of unpolarized radiation: an SI-8-200 tungsten lamp (for the spectral range 350–800 nm) and a DVS-25 gas-discharge hydrogen lamp (for the range 200–350 nm). The true spectral distribution for the SI-8-200 tungsten lamp was calculated from Planck's formula for a specified temperature T of lamp wire with allowance for the radiative properties of a gray body [9]. The spectrum recorded for the DVS-25 lamp was normalized to the theoretical spectrum from [10], after which it was matched with the intensity distribution for the SI-8-200 lamp. The thus obtained sensitivity curve for the recording system is shown (in absolute units) in Fig. 1.

The absolute photon yield from the electron-irradiated surface for a chosen wavelength was determined from the formula

$$N\left[\frac{\text{photons}}{\text{s nm}}\right] = \frac{I_{\text{exper}}(\lambda)S2\pi}{\beta(\lambda)S_{\text{exper}}I_{\text{el}}\Omega D\Delta l_{\text{exper}}}, \quad (1)$$

where $I_{\text{exper}}(\lambda)$ is the radiation intensity in relative units for a chosen wavelength λ, $\beta(\lambda)$ is the sensitivity coefficient of the recording system for this wavelength, S is the sample surface area exposed to electron beam, S_{exper} is the sample surface area from which radiation is collected, I_{el} is the electron beam current, Ω is the observation solid angle for radiation, D is the reciprocal linear dispersion of the MDR-12 monochromator, and Δl_{exper} is the width of the monochromator entrance slit.

RESULTS AND DISCUSSION

The measured IIPE and EIPE spectra of the silicon surface are shown in Figs. 2 and 3, respectively.

In both cases, two types of emission are observed: continuous emission in a wide wavelength range and characteristic emission in the form of spectral lines or bands. The IIPE spectrum contains wide continuous emission bands, peaking near λ_1 = 280 nm and λ_2 = 440 nm, and narrow silicon and helium lines: Si I 288.2, Si I 252.8, He I 388.9, He I 587.5, and He I 447.1. The silicon lines are due to excited Si atoms sputtered from the sample surface and the helium lines are due to bombarding He ions scattered from the surface and excited during scattering.

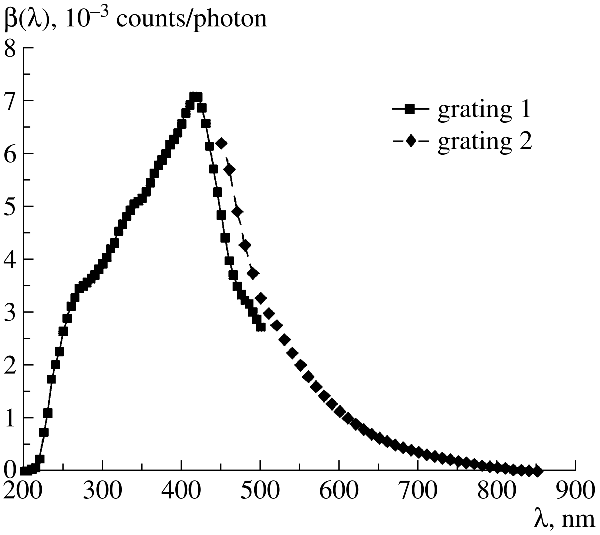

Fig. 1. Sensitivity curve of the recording system.

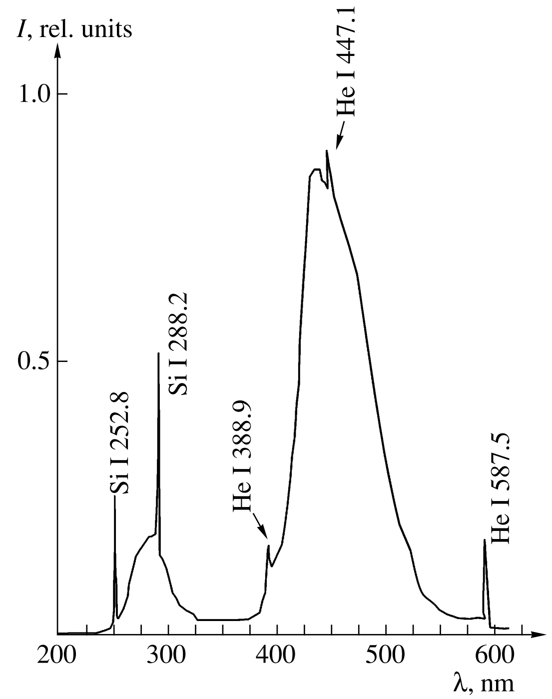

Fig. 2. IIPE spectrum of silicon (E_{ion} = 15 keV, I_{ion} = 2.4 mA cm^{-2}).

The EIPE spectrum of silicon contains a continuous emission band peaking at λ_1 = 280 nm, an OH molecular band at 308 nm, and hydrogen lines of the Ballmer series (H_α 657 and H_β 486). Analysis of the results obtained shows that the silicon surface, even at high vacuum in the working chamber, is effectively covered by residual gas particles. The absence of the OH band and hydrogen lines in the IIPE spectrum of silicon is explained by constant cleaning of the silicon surface as a result of ion-beam sputtering.

The continuous emission band at λ_1 = 280 nm, which is observed in both spectra, has apparently the same nature. Note that the energy position of the band maximum corresponds to the energy of photons emitted

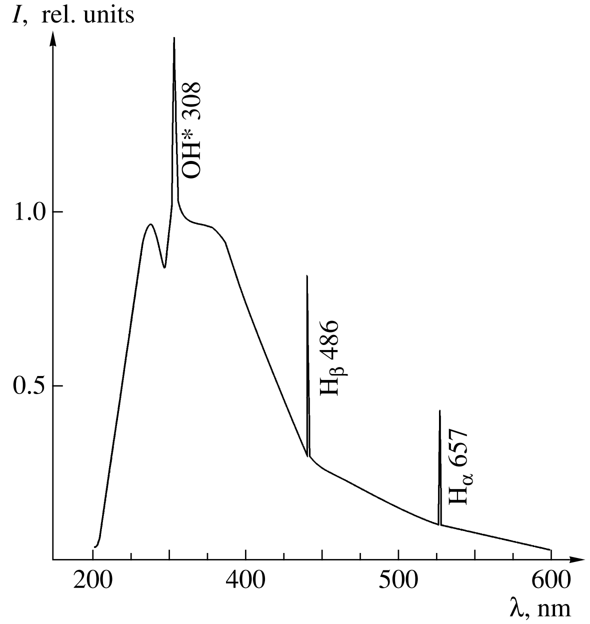

Fig. 3. EIPE spectrum of silicon (E_{el} = 800 eV, I_{el} = 7.6 mA cm^{-2}).

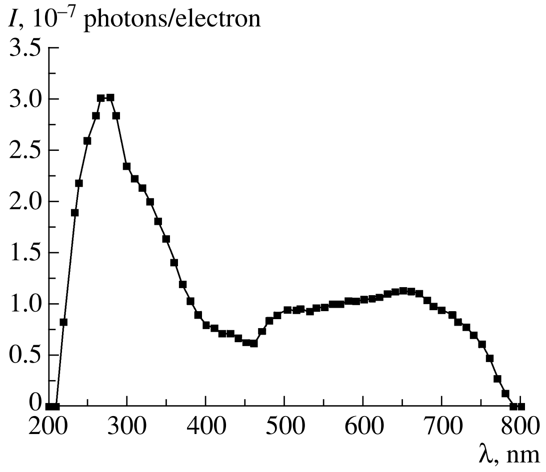

Fig. 4. EIPE spectrum of silicon in absolute units.

in interband transitions in Si [11, 12], in particular, transitions of electrons from surface electronic states to the bulk states of the Brillouin zone (S_4–Γ'_2). The peak at λ_2 = 440 nm, observed in the IIPE spectrum of silicon, also correlates with the energy of direct bulk interband transitions $\Gamma'_{15}-\Gamma'_{25}$ in the Brillouin zone [13].

Figure 4 shows the EIPE spectrum of silicon in absolute units, i.e., with allowance for the spectral sensitivity of the recording system.

Note the increase in the intensity at the periphery of the spectrum and a sharp decrease in the middle in comparison with the spectrum shown in Fig. 3. These changes are related to the fact that the maximum sensitivity of the FEU-106 detector lies in the range 400–450 nm. To determine the absolute photon yield from the silicon surface, we multiplied the values of continuous emission intensity (Fig. 4) by a wavelength range of 10 nm and then summed them. Thus, the absolute photon yield from the silicon surface per incident electron in the wavelength range 200–800 nm is $N \approx 6.9 \times 10^{-4}$ photons/electron.

CONCLUSIONS

The emission spectra in the ranges 200–800 and 200–600 nm under bombardment of single-crystal silicon surface by electrons and ions, respectively, was investigated. In both cases, two types of emission, differing in both its localization and generation mechanism, were observed: continuous and characteristic ones. The continuous emission is from the directly bombarded surface area; it is due to radiative relaxations of the excited electronic subsystem of the crystal, specifically electronic transitions from the surface states to the bulk states in the Brillouin zone (S_4–Γ'_2) and direct bulk interband transitions in the Brillouin zone ($\Gamma'_{15}-\Gamma'_{25}$). The characteristic emission, which is formed before the bombarded surface, is due to sputtered silicon atoms and scattered helium atoms (ion bombardment) or desorbed excited particles (electron-induced desorption).

The absolute photon yield from the silicon surface bombarded by 800-eV electrons (in the wavelength range 200–800 nm) was found to be 6.9×10^{-4} photons/electron; this value significantly exceeds the photon yield from metal surfaces but is still much lower than that for phosphors.

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