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Photofield emission from SiGe nanoislands under green light illumination

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ABSTRACT

Photofield emission from SiGe nanoislands formed by molecular beam epitaxy (MBE) have been investigated. Two types of nanoislands, namely the domes and pyramids with different heights, have been addressed. It was found that the arrays of SiGe nanoislands exhibited a low onset voltage for field emission. The increase of emission current and the decrease of the curve slope in Fowler-Nordheim coordinates under green light illumination have been revealed. Electron field emission and photoemission from SiGe nanoislands have been explained based on the energy band diagram of Si-Ge heterostructure and some energy barriers have been determined.

1. Introduction

Electron field emission and photofield emission from nanomaterials are currently under intensive investigation due to the necessity to determine the material parameters and further development of vacuum micro- and nanoelectronic devices [1–4].

To obtain high emission current, as a rule, the emitter arrays are used.

One of the promising directions of the formation of nano-objects for field emission purposes can be the process of self-organization in nonequilibrium systems [5–7]. During the deposition of germanium on silicon substrate with value of the lattice constant of Ge 4% bigger as compared to that of Si the film grows according to Stranski-Krastanov (S-K) mechanism [8,9]. The gist of it is that the first two-dimensional layer growth occurs, and only after certain critical film thickness (~4 monolayers) is achieved, the growth mode transfers to the formation of three-dimensional islands the so called 2D-3D conversion [10–12]. The peculiarity of such nanoislands is that they are non-dislocational at the early stages of their growth. Depending on the mode of an epitaxial process, including substrate temperature, deposition rate, nominal thickness of the deposited layer Ge (GeSi) islands may take the shape of a "hut" – clusters, pyramids and domes. Usually, formed nanoislands are laterally disordered. Presence of inhomogeneous mechanical tension in the majority of islands and in the adjacent buffer layers leads to a significant Si interdiffusion in the islands, and, thus to the formation of the islands with the composition SiGe [11,13].

Using Raman spectroscopy, we have established the composition of islands formed under different conditions [11,13]. Specifically, it is shown that islands that were formed at 600 °C have the Si content equal to 30% [13]. With the increase of the temperature of epitaxy, diffusion enhances significantly. We have shown that the content of silicon in the pyramids is slightly higher than in the domes, due to the presence of the stronger mechanical tension. Note, that for the process of field emission not only the average islands composition is important, but also the distribution of component in them. The distribution of silicon and germanium islands is established by us using local Auger spectroscopy. It is shown that the islands obtained by this MBE method at 700 °C are characterized by Ge core and SiGe shell [14]. It is expected that at the growth temperature of 600 °C the SiGe shell layer will be significantly thinner due to lower diffusion coefficient of Si.

The results of electron field and photofield emission from SiGe self-assembled nanoislands on Si substrate are presented here.

2. Experimental

SiGe nanoislands were performed by molecular beam epitaxy on Si (100) substrate with a 200 nm thick Si buffer layer [13]. The thickness of the Ge layer, d_{Ge} was 6 monolayers (ML) and the growth

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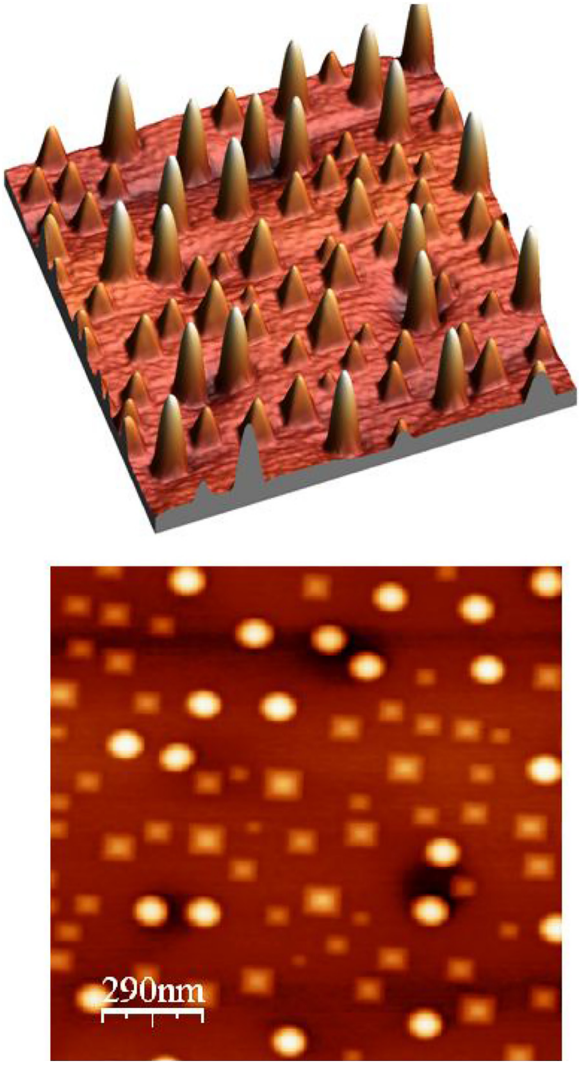

Fig. 1. AFM image of SiGe nanoislans on Si substrate.

temperature was 600 °C. The first 4 monolayers of Ge grow layer by layer on Si. However, as the number of Ge layers exceeds the critical thickness of 4 ML, the lattice strain cannot be accommodated and the island formation becomes energetically favorable. The atomic force microscopy (AFM) topography of the experimental sample is shown in Fig. 1. As can be seen, the distribution of islands on heights is bimodal, also observed in a number of published works [14–17]. AFM image of the sample surface shows the conical and pyramidal nanoislands (Fig. 1). The average height of the pyramids is of 3 nm, and that of the domes is of 10 nm, respectively. The angles at the base are of 10° and 26° for the pyramids and the domes, respectively.

The composition of islands was investigated by Raman spectroscopy, which is an informative method for studying semiconductor nanoobjects. Besides the intensive Si-Si line from Si substrate ($\omega_{Si\text{-}Si}$ = 520.5 cm^{-1}), the Raman spectrum consists of three peaks related to the Ge-Ge ($\omega_{Ge\text{-}Ge}$ = 294 cm^{-1}), Ge-Si ($\omega_{Ge\text{-}Si}$ = 412 cm^{-1}) and Si-Si ($\omega_{Si\text{-}Si}$ = 495 cm^{-1}) vibrations of atoms in the islands [13,18]. The knowledge of these phonon frequencies allows us to determine the composition x and the elastic strain ε in $Si_{1\text{-}x}Ge_x$ nanoislands. The Ge content and the elastic strain in the islands, measured by this method within the limits of a measurement error were in good agreement with the results obtained by X-ray diffraction [13]. The nanoislands in our case were not pure germanium but comprised of about 70% of Ge and 30% of Si. One should note that these values are the average values since there the islands have different shapes and volumes and there is a distribution of Si atoms from bottom to top in a separate island.

The electron field and photofield emission from SiGe nanoislands have been studied. The field-emission setup used for the measurements could be pumped out to a vacuum of 4×10^{-7} mbar. The flat diode electrode configuration was used. The cathode electrode was SiGe nanoislands formed on Si substrate. Indium-tin-oxide (ITO) coated quartz plate was used as the anode electrode. The distance between the emitter and ITO anode was defined by a 7.5 μm thick kapton spacer and emission current passed through a hole of 1 mm in diameter. The light of a laser placed outside was focused onto the field emitter in a high-vacuum chamber through the quartz glass. Green laser diode with the wavelength λ = 532 nm (P = 5 mW) was used for the photoassisted field emission measurements [3]. We used continuous illumination by laser light (no pulse). The excitation intensity was of 2.55×10^2 W/m^2.

3. Results and discussion

The energy band diagrams of investigated structure are shown in Fig. 2. To calculate the value of the energy bandgap of $Si_{1\text{-}x}Ge_x$ islands the equation obtained in Ref. [19] has been used:

$$E_g(x, 4.2K) = 1.155 - 0.43x - 0.206x^2 \quad (1)$$

where x is the Ge content (in our case 0.7). To estimate the $Si_{1\text{-}x}Ge_x$ bandgap at higher temperatures (room temperature in our case, T = 300 K), one can modify the well-known temperature dependence of the bandgap value of Si as shown below [20,21].

$$E_g(x, T) = E_g(x, 0K) - \frac{4.73 \times 10^{-4} T^2}{T + 636}^2 \quad (2)$$

The energy gap at T = 0 K was approximated by value at T = 4.2 K. The obtained value of $Si_{1\text{-}x}Ge_x$ (x = 0.7) bandgap value at 300 K is $E_g(Si_{1\text{-}x}Ge_x)$ = 0.708 eV.

The value of the valence bands offset between pure Ge and Si equal to $\Delta E_v(Si\text{-}Ge)$ = 0.74 eV has been taken into account [20,22]. The linear interpolation of the valence band offset in Si/SiGe heterostructures with respect to Ge composition was accepted to calculate $Si/Si_{1\text{-}x}Ge_x$ systems [20,23–26]. The value $\Delta E_v(Si\text{-}SiGe)$ = 0.52 eV has been obtained. Based on $E_g(SiGe)$ and $\Delta E_v(Si\text{-}SiGe)$ values, we reproduced the energy band diagrams of Si-SiGe system under investigation [Fig. 2a)]. More precise energy band diagram has to include energy band widening due to the quantum confinement effect [27,28]. The obtained in this case energy parameters are shown in Fig. 2a) in round brackets. As was mentioned earlier, obtained by Raman spectroscopy content of Ge in SiGe nanoislands is averaged. In our analysis we suggested that the top of the islands is a Ge layer deposited during the last stage of the epitaxial process.

According to the Fowler-Nordheim theory [29] the current density at field emission J depends on the electric field at the surface E and the work function Φ according to the following equation:

$$J(0) = \frac{e^3 E^2}{8\pi h \Phi t^2(y)} \times \exp\left[-\frac{8\pi(2m)^{1/2}\Phi^{3/2}}{3heE} v(y)\right] \quad (3)$$

where h is the Planck's constant, e is the electron charge, E is the electric field, Φ is the work function, and $v(y)$ and $t(y)$ are the elliptic integrals of the following parameter:

$$y = (e^3 E)^{1/2} / \Phi \quad (4)$$

In some cases, it is possible make rather good approximation of $v(y)$ and $t(y)$ as:

$$t^2(y) \approx 1.1 \text{and} v(y) \approx 0.95 - y^2 \quad (5)$$

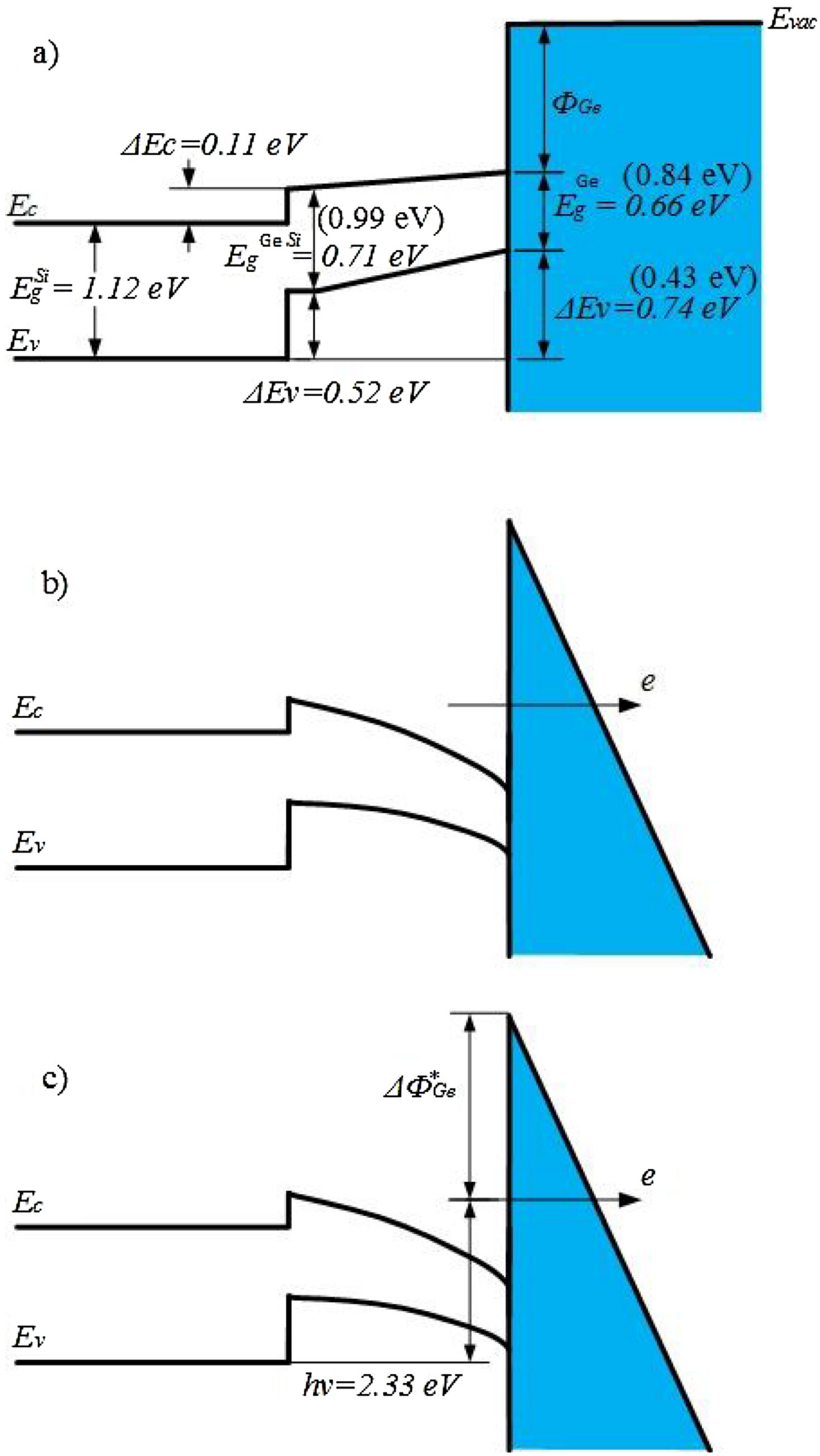

Fig. 2. Schematic representation of the energy band diagrams of Si-SiGe heterostructure: a) – without electric field; b) – with electric field; c) – with electric field and under green light (*l* = 532 nm, *hn* = 2.33 eV) illumination. The values obtained with taking into account quantum confinement effect are shown in round brackets.

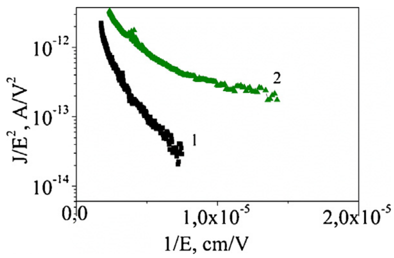

Fig. 3. Emission current-voltage characteristics in Fowler-Nordheim coordinates of SiGe nanoislands without (1) and with (2) green light illumination.

Typically, the field emission current I is measured as a function of the applied voltage V and $J = I/\alpha$ and $E = \beta V$, where α is the emitting area and β is the local field conversion factor at the emitting surface, can be substituted in Eq. (3). Combining these relationships one obtains [30].

$$I = aV^2 \exp(-b/V) \quad (6)$$

where

$$a = \frac{\alpha A \beta^2}{1.1\Phi} \times \exp(\frac{1.14 \times 10^{-7} \times B}{\Phi^{1/2}}), \quad (7)$$

$$b = 0.95B\Phi^{3/2}/\beta \quad (8)$$

$B = \frac{8\pi(2m_0)^{1/2}}{3he}$, and b is the curve slope, respectively.

In the processes of electron field emission analysis the electron field enhancement coefficient β^* is often used instead of the local field conversion factor β. They are related each to other as $\beta^* = \beta \times L$, where L is the anode-cathode spacing. The parameter b can be determined from the curve slope in the Fowler-Nordheim coordinates $ln(I/V^2) - 1/V$. In general case it is impossible to separate two unknown parameters β and Φ in Eq. (8) [30–32]. However, comparing electron field emission and photofield emission it is possible to estimate the ratio of Φ_{Ge}/Φ_{Ge}^* based on Eq. (8):

$$\frac{\Phi_{Ge}}{\Phi_{Ge}^*} = (\frac{b_1}{b_2})^{2/3} \quad (9)$$

where b_1 and b_2 are the slopes of emission current-voltage characteristics in Fowler-Nordheim coordinates without and with light illumination, respectively.

Due to the barrier for electron field emission from the valence bands of Si, SiGe and Ge are significantly higher the barriers at emission from conduction bands in our analysis we used work function equal to the electron affinities ($\Phi \equiv \chi$). The energy band diagram presented in Fig. 2a) allows one to determine the electron affinity of Ge using the well-known value of $\chi_{Si} = 4.05$ eV [33]. The obtained value of electron affinity of Ge is $\chi_{Ge} = 3.77$ eV.

Experimental electron field emission and photofield emission curves in Fowler-Nordheim coordinates are presented in Fig. 3. As can be seen from this figure, there are two slopes on each curve (in high voltage and low voltage regions, respectively). The existence of two slopes of the curve is caused by electron field emission from higher cones ($h \approx 10$ nm) at low voltages with following involving of the electron tunneling from lower pyramids ($h \approx 3$ nm) in the emission process at higher voltages. In the case of electron field emission, the onset voltage of 217 V ($E_{on} = 2.9 \times 10^5$ V/cm) for a 10 nA emission current level and total current as large as of 1 μA at 303 V are observed. The light illumination increased the total emission current significantly:- up to the value of 530 μA at 325 V. The slopes of electron field and photofield emission curves in Fowler-Nordheim coordinates in the high-voltage region (Fig. 3) are $b_1 = 1128$ and $b_2 = 470$, respectively.

The current increased immediately upon the illumination of emitter and then reached the value up to two orders of magnitude higher than the initial current. Illumination also results in the generation of electron-hole pairs by absorption of green light photons with energies above the bandgap of the SiGe nanoislands (0.71 eV, see Fig. 2). Electrons can then reach the surface quickly due to the small size of nanoislands. In the case when the SiGe islands are not illuminated, the emission takes place from the bottom of the conduction band ($\Phi \equiv \chi = 3.77$ eV). If we take into account quantum confinement effect for smaller nanoislands ($h \approx 3$ nm) the value of $\chi = 3.90$ eV. With illumination with green light, new electrons are generated from the valence band and occupy the upper energy levels in the conduction band. The main emission occurs from these levels, which has lower electron emission barriers. The electron emission energy barrier difference can be calculated by evaluating the two slopes b of the Fowler-Nordheim characteristics. The barrier height ($\Phi_{Ge}^* = \chi_{Ge}^*$) at photofield emission has been estimated according to Eq. (9). Obtained value of Φ_{Ge}^* is of $\Phi_{Ge}^* = 2.09$ eV and with taking into account quantum confinement effect $\Phi_{Ge}^{*'} = 2.17$ eV. As it can be seen, the discrepancy in values of Φ_{Ge}^* is 0.08 eV.

Comparison of Fig. 2b) and 2c) allows one to determine the bandgap of SiGe nanoislands in their top parts according to the following equation:

$$\Phi_{Ge}^* = \Phi_{Ge} - (h\nu - E_g) \quad (10)$$

Obtained value of E_g is equal to $E_g = 0.65$ eV, which corresponds to the bandgap value of Ge equal to $E_g(Ge) = 0.66$ eV [33].

Based on the investigations of electron field and photofield emission, it became possible to prove that the top of SiGe nanoislands is significantly enriched with Ge.

The slopes of the curve in Fowler-Nordheim coordinates allowed one to determine the electric field enhancement coefficients (β^*) for the known work function of Ge ($\Phi = 3.77$ eV). The coefficients β^* were determined from Eq. (8). The obtained value is $\beta^*_1 \approx 228$. During electron photofield emission the electric field enhancement coefficient remains the same. It allows to determine the $\Phi_{Ge}^* = \chi_{Ge}^*$ according to Eq. (8) at measured slope of photofield emission curve ($b_2 = 470$). The obtained value is $\Phi_{Ge}^* = 2.18$ eV. It is in a good agreement with the value calculated on the base of the energy band reconstruction ($\Phi_{Ge}^* = 2.09$ eV). The analysis of electron field and photofield emission in such way allowed one to estimate some energy parameters of nanostructures.

4. Conclusions

During investigation of electron field and photofield emission from self-assembled SiGe nanoislands formed by MBE on Si substrate the efficient electron field emission has been observed. Field emission current up to 1 μA has been obtained at 303 V with the onset voltage as low as 217 V ($E_{on} = 2.9 \times 10^5$ V/cm). Photofield emission current under green light illumination was significantly higher (530 μA at 325 V). Analysis of experimental results allowed one to determine the electron affinity of Ge and confirmed that the top of SiGe nanoislands is significantly enriched with Ge.

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