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# Influence of electron irradiation on spectra of light electroreflection from the surface of $Ge/Ge_{1-x}Si_x$ heterostructure

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**Abstract.** In this work, the growth properties of $Ge_{1-x}Si_x$ epitaxial films grown on Ge substrates were investigated. The structural perfection of the films was controlled by electron diffraction, electron microscopic and X-ray diffraction methods. It has been established that the surface structure of the sample $Ge/Ge_{1-x}Si_x$ changes after irradiation by accelerated electrons $\Phi = 5{\cdot}10^{16}$ $cm^{-2}$, and generated are surface defects which play the role of traps for change carriers.

**Keywords:** germanium-silicon alloy, epitaxial film, heterostructure, optical absorption, electroreflection.

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## 1. Introduction

Recently interest in periodical structures based on Ge and Si:Ge/$Ge_{1-x}Si_x$ [1, 2] has increased. These structures referred to a class of superlattices with strained layers allow to essentially expand the opportunities of initial materials [3] traditionally used in practice as well as are of interest, in particular for detectors of infrared [4] and millimeter ranges of wavelengths. Besides, the possibility to observe quantum size effects with their perspectives in electronics is now widely discussed [5] and can be pronounced in the structures with hyperfine layers at low temperatures.

## 2. Experimental

In this work, the singularities of the growth of $Ge_{1-x}Si_x$ epitaxial films grown on Ge (111) substrates by the method of molecular-beam condensation in vacuum $10^{-4}$ Pa and preparation of photosensitive *p-n* junctions on their basis are investigated.

With this aim, optimal conditions were developed to obtain structurally perfect ($W_{1/2} = 90\ldots100$ arc sec – half-width of the rocking curve in X-ray diffraction) epitaxial films $Ge_{1-x}Si_x$ possessing *p*- and *n*-types of conductivity with the thickness 0.5…1 µm, concentration ($(n, p_{77\,K}) = 1{\cdot}10^{16}\ldots1{\cdot}10^{17}\,cm^{-3}$) and charge carrier mobility ($\mu_{n,p}(77\,K) = (2.5\ldots3){\cdot}10^4\,cm^2/V{\cdot}s$). The epitaxial films were grown on Ge (111) substrates at the condensation rate $\upsilon_c = 8\ldots10$ Å/s and temperature of the substrates $T_s = 653\ldots673$ K.

The thickness of separate layers in the superlattice was 2 to 20 nm in comparison with its total thickness 2 to 4 µm, the content of Si in alloy layers was 5…15 %.

Structural perfection of the films was controlled by electron diffraction, electron microscopic and X-ray diffraction methods (Fig. 1). For the purpose of obtaining the films with *n*- and *p*-type conductivity, perfect structure and necessary electrophysical parameters, an additional compensating vapor from a Sb source was used in the growth process [3].

One of the methods to reduce the density of surface defects is preparation of active elements in the same technological cycle. By this way, *p-n* homostructures were obtained as intersecting bands in one technological cycle without vacuum deterioration. After deposition of the first system of bands *p*-$Ge_{1-x}Si_x$, the baffler was closed, and in a certain time after establishment of the necessary temperature conditions and mask displacement, the baffler was opened again, and the second system of *n*-$Ge_{1-x}Si_x$ bands was deposited.

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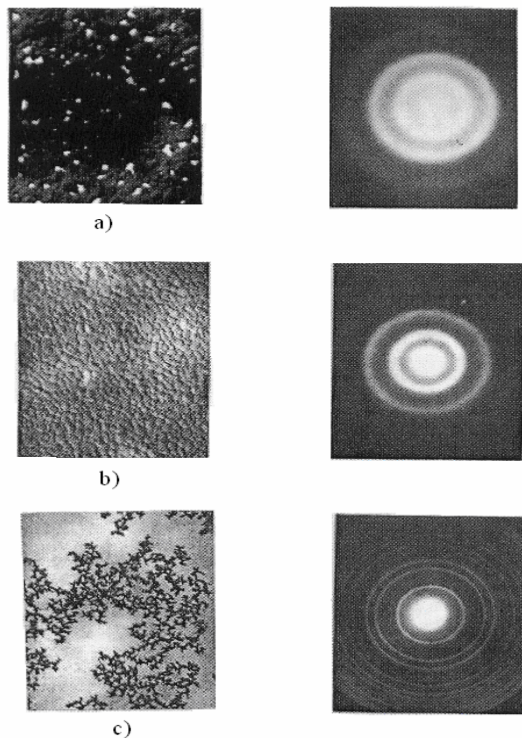

**Fig. 1.** Microphotos and electron diffraction patterns of the films $Ge_{1-x}Si_x$ (x = 0.15), $d$ = 100 nm; $T_s$ = 490 K (a), 500 K (b), 530 K (c). Magnification ×3500.

## 3. Results and discussion

The explanation of the effects observed during the experiments [5] as well as creation of fundamentally new devices based on the obtained structures demands a reliable control of the parameters of deposited layers and development of methods for determining the characteristics of electron gas in them. One of the suitable methods for the superlattice $Ge_{1-x}Si_x$ grown on Ge substrates to investigate periodic potential and electron energy band spectrum, which requires no application of complicated apparatus, is the method of light electroreflection from the surface of semiconductor [6].

The samples were irradiated using a linear electron accelerator of ELA-6 type with the nominal output energy 4.5 MeV. The accelerator operated with the frequency 50 Hz and pulse duration 2.5 ms. Besides, the average current of the accelerated electrons, by which the sample was irradiated, equaled to 2 μA. The sample was irradiated via a cryostat window covered by a beryllium foil with the thickness 100 μm.

In this work, the spectra of light elecroreflection from the surface of periodic semiconductor structures $Ge/Ge_{1-x}Si_x$ with various periods were measured in the near IR spectral range and analyzed. Their distinctive features were revealed in comparison with the spectra of light electroreflection from thick layers of solid solution $Ge_{1-x}Si_x$. The possibility to use this method for diagnostics of separate parameters of the superlattice was shown. An essential difference in the characters of the spectra of light electroreflection from the structure with tunnel transparent and opaque potential barriers was found out.

Some parameters of the obtained structures are summarized in Table. The mean concentration of Si in the superlattice ($x_{sl}$) and amplitude of Si content variations in neighboring layers (Δx) were determined by the method of X-ray diffraction analysis. The measurement procedure of the spectra of light electroreflection from the surface of the samples differed from that applied before in the work [7] according to the use of ditch with capillary layer of electrolyte. It made possible to carry out measurements in the neighborhood of lower bound of fundamental absorption band. In the near IR spectral region (0.7…1.2 eV), the depth of light penetration into crystal was of the order of several tens of micrometer in comparison with a visible frequency band [8], which allows determining the properties of the superlattice as a whole.

Let's assume that this periodic system is characterized by sufficiently perfect boundaries of heterojunctions $Ge/Ge_{1-x}Si_x$ (the thickness of the transition region is much smaller than that of a separate layer). Then the potential relief can be approximated by alternate rectangular wells separated by sufficiently thick barriers excluding the effect of tunneling. It's evident that the spectra of light electroreflection from such a system should possess the properties inherent to the spectra of electroreflection from the separate layers Ge and $Ge_{1-x}Si_x$. Let us analyze how this model agrees with the experimental results obtained for the specific structures with thick enough layers (Fig. 2). The spectra of light electroreflection from the structures *1* and *4* possess series of well-allowed (broadening parameter is close to 10 meV) resonance peaks relatively shifted from one another. The resonance peak $E_{01}$ is connected with direct (at a point κ = 0) transitions in the layers Ge, the peak $E_{02}$ – in the layers $Ge_{1-x}Si_x$. The spectra of light electroreflection from the surface of the superlattice on the surface of thick (4 to 8 μm) alloy layers $Ge_{1-x}Si_x$ (Fig. 3) differ from each other by a total number and relative position of resonance peaks.

**Table. Composition and parameters of the samples**

| Sample | Percentage Si (at.%) | Initial concentration of the carriers at 77 K ($cm^{-3}$) | Mobility $\mu_0$, $cm^2/V\cdot s$ | $d$, nm | Specific resistance ρ (Ohm·cm) at $T$ = 293 K |
|---|---|---|---|---|---|
| 1 | 0 | $1.43\cdot10^{15}$ | $3\cdot10^4$ | 135 | 1.38 |
| 2 | 5 | $1\cdot10^{16}$ | $2.75\cdot10^4$ | 132 | 1.45 |
| 3 | 10 | $1.37\cdot10^{16}$ | $2.62\cdot10^4$ | 130 | 3.0 |
| 4 | 15 | $1.0\cdot10^{17}$ | $2.5\cdot10^4$ | 120 | 6.45 |

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The comparison of the curves in Figs 2 and 3 shows that elastic stress present in the layers of the periodic structure shifts the position of the resonance peaks. The low-energy boundary of absorption region caused by direct electron transitions in Ge layers is shifted to much more shortwave spectral region.

The spectra of reflection of Ge-Si were investigated in the works [3, 9, 10]. The analysis shows that the first maximum for Ge lies in the region 2.0 to 2.3 eV, and for Si – in the vicinity of 3.3 eV. The first maximum in the solid solution Ge-Si is between these maxima, in dependence on the content of Si.

In the work [11], it has been shown that the effective mass of current carriers determined using infrared reflection spectra in the solid solution Ge-Si doesn't depend on the concentration of the carriers as a concentration function and corresponds to the absolute values of the electron effective mass in Si, which agrees with the character of the band structure for the solid solutions Ge-Si.

The thin structure of the spectra of light electroreflection from the surface of the samples *1*, *4* (Fig. 2a; the spectrum for the sample *4* is similar to that for the sample *1*), apparently, is connected with splitting of degenerate states of the valence band at the point $\kappa = 0$ under the action of deformation breaking the symmetry of crystal lattice in a separate layer. The splitting value of the peaks $E_{01}$-$E_{01}$ ($E_{02}$-$E_{02}$) in the spectra of light electroreflection (Fig. 2a, d) for the investigated samples varies within the range of several hundreds of electron-volt, which corresponds to elastic stress values in the layers $\sigma \sim 10^8 \ldots 10^9$ Pa [10].

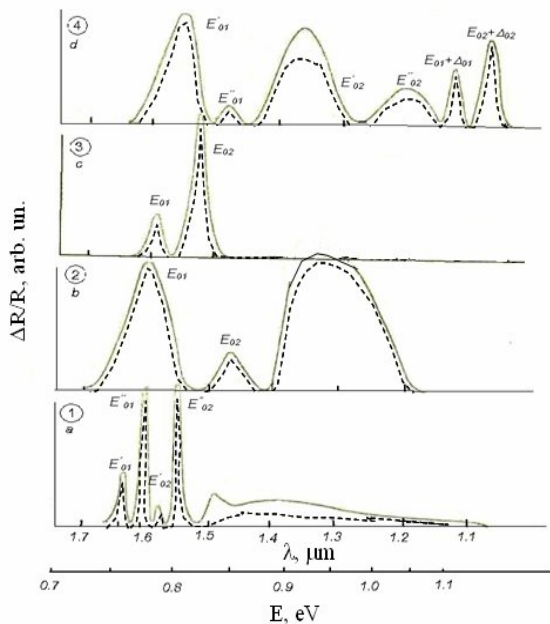


**Fig. 2.** Spectra of electroreflection for heterostructures Ge/$Ge_{1-x}Si_x$ before and after irradiation. Solid line before irradiation. *1* – x = 0; *2* – x = 0.05; *3* – x = 0.10; *4* – x = 0.15; $\Phi = (1\ldots5)\cdot10^{16}$ cm$^{-2}$.

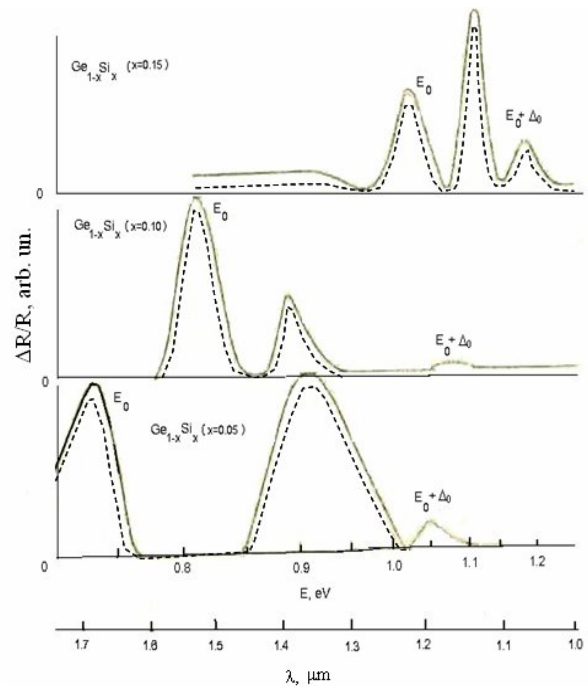


**Fig. 3.** Spectra of electroreflection of $Ge_{1-x}Si_x$ alloy samples before and after irradiation. Solid line – before irradiation. $\Phi = (1\ldots5)\cdot10^{16}$ cm$^{-2}$.

The reduction of the superlattice period without change of Si content in the layers leads to broadening the peaks in the electroreflection spectra in consequence of relative increase of the role of reflected light from transition regions. The thin structure of the resonant peaks $E_{01}$ (2) in spectral curves may vanish (Fig. 2c). The rise of Si concentration in the layers $Ge_{1-x}Si_x$ (compare the curve *d* in Fig. 2 with the ones *a*, *c*) displaces the resonant peak $E_{02}$ to the side of high energies, increases the broadening parameter and the size of valence band splitting at the point $\kappa = 0$, which result in rise of the number of resonant peaks in spectral curves. For the simplicity of comparison, the amplitudes of separate peaks were multiplied by the correspondent factor in the dependences $\Delta R(\lambda)/R(\lambda)$. Shown in Fig. 2b is the spectrum of light electroreflection from the sample *2* differing by a higher Si content but a low amplitude of its variation ($\Delta x \sim 2$ %) in the neighboring layers. An essential broadening (up to 50 meV) the resonance peaks is apparently conditioned by considerable (in comparison with *d*) rise of transition regions' sizes. It's evident that deviation from periodicity of the system should lead to broadening the spectral maxima, too.

Thus, in a general case the quality and some electron characteristics of the obtained structures can be determined using the spectra data of light electroreflection and the value of the broadening parameter for resonant bands. Besides, the difference of peaks' positions $E_{02}$-$E_{01}$ allows evaluating the total (for conductivity band and valence band) amplitude $\Delta U$ of

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the potential relief taking into account the stress in the structures. It equals to $\Delta U$ ~ 0.02…0.03 eV for the structures *1*, *3* and $\Delta U$ ~ 0.1 eV for the structure *4*. The value of the potential amplitude in the spectra of light electroreflection in the visible spectral range gives the same order of magnitude at sequential etching the layers [7].

The negative differential conductivity in current-voltage characteristics of this periodic structure at current flowing along the layers of the superlattice can also occur as a result of transversal diffusion of charge carriers from Ge layers with a high mobility to the neighboring alloy layers with a low mobility [3]. In the reverse situation (the main charge carriers are concentrated in the layers of solid solution), a superlinear current-voltage characteristics appears.

Superlinearity or sublinearity of the current-voltage characteristics is connected with electron transitions between split bands when heating as a consequence of elastic stress in the system, and it can be one of the probable reasons for high nonlinearity occurrence in the high-frequency characteristics observed in the experiments [10].

The measurement has shown that there is an absorption band for pure germanium in the vicinity of λ = 24.2 μm (Fig. 4). Absorption bands close to 21.0, 20.8 and 20.6 μm are correspondingly revealed for the samples with 5, 10 and 15 atomic percents of silicon. As it is evident, the absorption peaks for the solutions with different contents of silicon are very close. The absorption spectrum shifts in the direction of short wavelengths with rise in the content of silicon. A significant increase of the absorption coefficient in thin films in the range of short wavelengths in comparison with pure germanium apparently indicates a cluster nature of the vibrational spectrum [11].

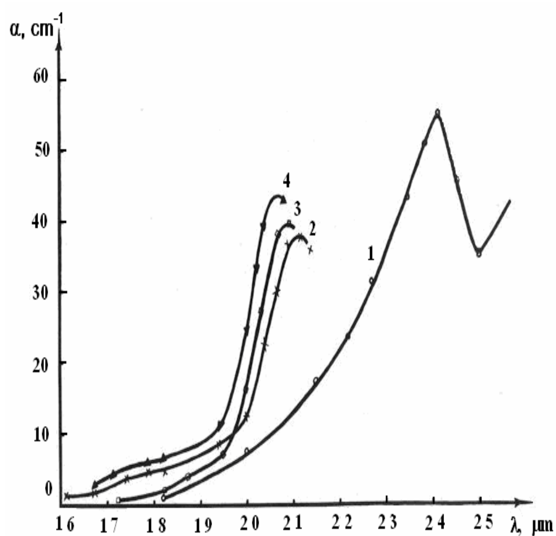


**Fig. 4.** Dependence of lattice absorption coefficient on the light wavelength: *1* – for pure germanium; *2*, *3*, *4* – for solid solution with 5, 10 and 15 at.% of silicon, accordingly.

In the works [8, 11-13], absorption within the range 9 to 48 μm was studied. In the alloy Ge-Si, besides absorption inherent to pure germanium and silicon, new absorption bands 214 and 508 $cm^{-1}$ that are less sensitive to changes of the alloy content, but demonstrate some changes observed in their shape and height (Fig. 4).

## 4. Conclusions

Investigation of electroreflection spectra for thin epitaxial Ge-Si layers shows that the number of peaks and their amplitude change as a result of electron irradiation of the samples. These changes can be explained by appearance of surface structural defects in the course of irradiation, which serve as traps for charge carriers.

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