08

Metastable states in the electronic subsystem of GaAs/$Al_xGa_{1-x}As$ heterostructures for quantum well infrared photodetectors

© *S.A. Kolosov, V.S. Krivobok, D.A. Pashkeev*

Lebedev Physical Institute, Russian Academy of Sciences, Moscow, Russia
E-mail: krivobok@lebedev.ru

Received August 28, 2024
Revised October 6, 2024
Accepted October 10, 2024

A metastable rearrangement of transport properties as well as photoresponse in the far IR spectral range was detected for a GaAs/$Al_xGa_{1-x}As$ heterostructure with silicon-doped quantum wells upon short-term illumination with near-IR emission. It is shown that this effect is associated with silicon *DX* centers formed in the vicinity of the GaAs/$Al_xGa_{1-x}As$ interfaces.

Keywords: R photodetector, quantum well, *DX*-center, molecular beam epitaxy.

DOI: 10.61011/TPL.2025.02.60631.20095

Semiconductor GaAs/$Al_xGa_{1-x}As$ heterostructures (HSs) with quantum wells (QWs) are used in the fabrication of photodetector devices (PDDs), including array ones, for middle and far infrared (IR) radiation spectrum regions [1–3]. A photon is detected due to the transition of an electron from the ground quantum-dimensional level (E_{1e}) to the first excited level (E_{2e}), which is located near the bottom of the barrier conduction band, and its subsequent drift in an external electric field [3]. Selective doping of GaAs QWs with silicon is commonly used to fill the E_{1e} level with electrons, since this impurity is technologically convenient for the GaAs/$Al_xGa_{1-x}As$ system. It is demonstrated in the present study that under certain conditions, impurity silicon may form metastable states near the interfaces of GaAs QWs, which lead to anomalous (metastable) rearrangements of the photoresponse in the far IR range. The observed effect may be significant for a wide range of applications where GaAs/$Al_xGa_{1-x}As$ HSs are used at cryogenic temperatures.

The GaAs/$Al_xGa_{1-x}As$ ($x = 0.27$) HS with QWs discussed in the present study was grown by molecular-beam epitaxy on semi-insulating GaAs (100) substrates at a temperature of 620°C. The thickness of $Al_xGa_{1-x}As$ barriers was 50 nm, and the thickness of GaAs QWs was 5.5 nm. A δ-layer of silicon with a concentration of $1.5 \cdot 10^{11}\,cm^{-2}$ was located at the center of each QW. GaAs layers with a thickness up to 200 nm doped with silicon to $10^{17}\,cm^{-3}$ were used to form top and bottom contacts. The growth process was discussed in more detail in [4]. The compliance of the HS parameters with the nominal ones was confirmed via X-ray diffraction analysis. The single-electron QW spectrum was estimated based on the measurements of luminescence spectra and photoluminescence excitation spectra. Specifically, the distance between levels E_{2e} and E_{1e} was 145 meV, which corresponded approximately to the maximum photoresponse of the photosensitive element (PE) at a wavelength of $\sim 8.6\,\mu$ fabricated from the obtained HS. The PE size was 2×1 mm. The steady-state PE photoconductivity spectra were measured at temperatures of 67–300 K using a grating monochromator fitted with a globar [5].

Figure 1, *a* illustrates the emergence of a metastable component in the HS conductivity. When the PE was cooled in the dark to a temperature of 67 K, the dark current through it was 11.6 μA at a voltage of 0.25 V. Irradiation of the PE with low-intensity light with wavelength $\lambda_i = 700$ nm for 500 s led to a gradual increase in current through the sample to 32.6 μA (with further irradiation, the growth continued, and the signal became saturated gradually). When illumination was turned off, the current through the PE decayed exponentially to $\sim 25\,\mu$A; after that, it remained virtually unchanged for more than two hours. The persistent component of dark current was near-zero at $\lambda_i > 1000$ nm and arose at $\lambda_i \sim 950$ nm (Fig. 1, *b*). To suppress the additional dark current stimulated by illumination, the PE needs to be heated and then cooled again. An example of the corresponding temperature dependences of resistance is shown in Fig. 1, *c*. Note that during both heating and cooling, the activation energy calculated from the slope of the temperature dependences of resistance within the range of 90–115 K has the same magnitude of ~ 145 meV, which matches the $E_{1e}-E_{2e}$ transition energy in the QW. At the same time, the PE resistance in the dark at temperatures below 90 K depends on the sample history.

Let us examine the influence of the above-described metastable effects on the current–voltage curves (Fig. 1, *d*) and the photoresponse spectrum in the far IR range (Fig. 1, *e*) at a temperature of 67 K. Curve *1* in Fig. 1, *d* was obtained before PE irradiation, while curve *2* was recorded after PE irradiation at $\lambda_i = 700$ nm. It can be seen that irradiation has a significant effect on conductivity, but the shape of current–voltage curves remains essentially unchanged. The shape of photoconductivity spectra in the far IR range also does not change in any significant way

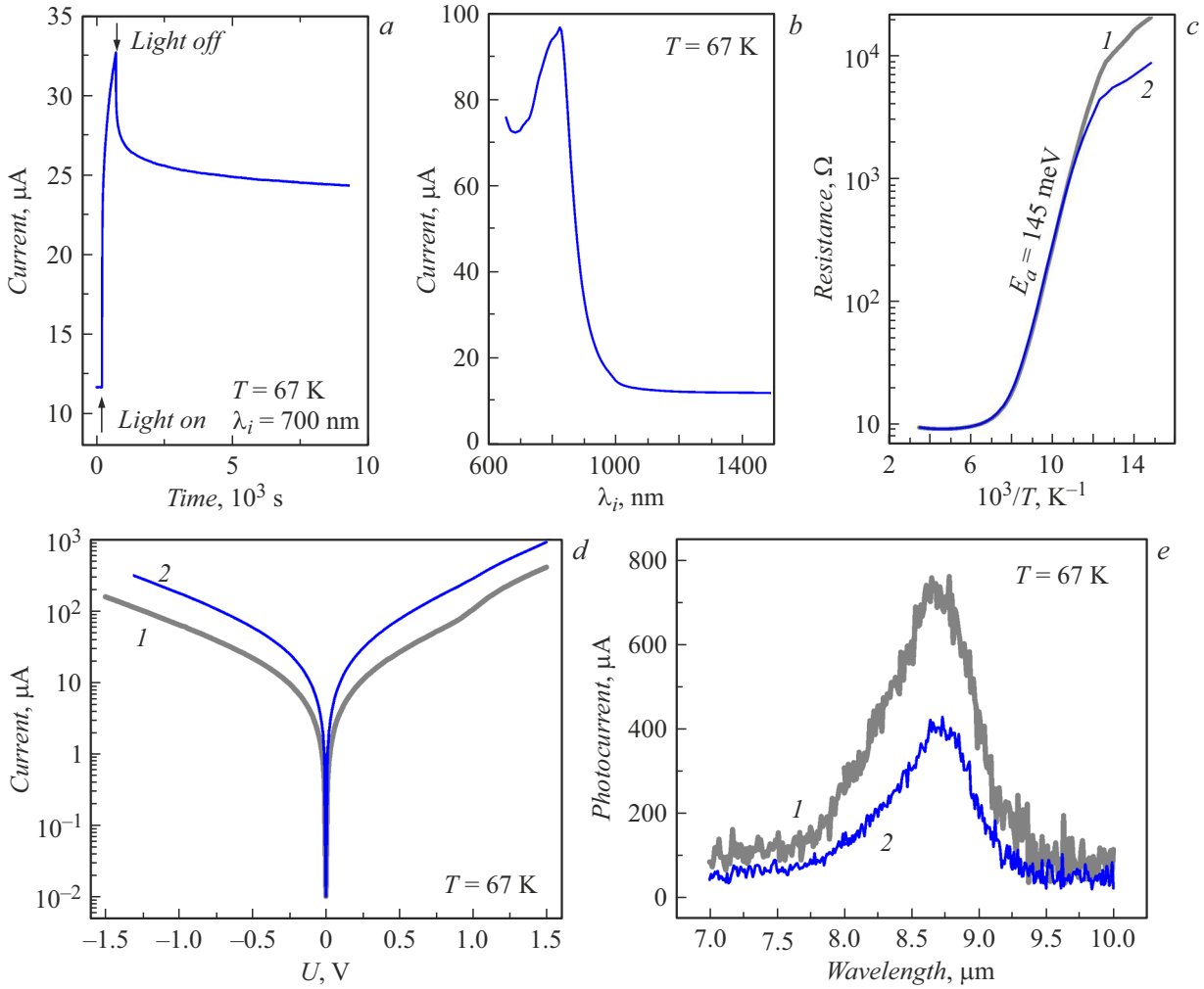

Figure 1. *a* — Emergence of a metastable component in conductivity of the HS irradiated with low-intensity light with $\lambda_i = 700$ nm for 500 s. $T = 67$ K. *b* — Dependence of the persistent photocurrent on λ_i at $T = 67$ K. *c* — Temperature dependences of the PE resistance under cooling in the dark (*1*) and heating of an initially cold PE irradiated with light with $\lambda_i = 700$ nm (*2*). The voltage drop across the sample is $U = 0.25$ V. *d* — Current–voltage curves of the PE obtained after its cooling to $T = 67$ K in the dark (*1*) and subsequent irradiation with light with $\lambda_i = 700$ nm (*2*). *e* — Photoconductivity spectra of the PE obtained after its cooling to $T = 67$ K in the dark (*1*) and subsequent irradiation with light with $\lambda_i = 700$ nm (*2*).

(Fig. 1, *e*), but a marked (approximately twofold) reduction in the signal intensity was noted.

The above-described rearrangement of transport properties of the HS caused by short-wave illumination is qualitatively reminiscent of the phenomena associated with the formation of so-called *DX* centers in $Al_xGa_{1-x}As$ solid solutions. These centers are produced as a result of capture of an additional electron by a neutral donor, which is accompanied by lattice relaxation and the formation of a deep trap [6]. Note that impurity silicon forms a stable *DX* center in $Al_xGa_{1-x}As$ solid solutions at $x > 0.22$ [6]. The non-decaying component of photocurrent is induced by photoionization of *DX* centers: $DX + \hbar\omega \rightarrow Si_{Ga^+} + 2e^-$, where Si_{Ga^+} is a positively charged silicon donor and e^- is a free electron. The metastable nature of emerging states stems from the fact that electron recapture requires overcoming a high potential barrier. It can be seen from Fig. 1, *b* that the threshold wavelength at which the persistent photoresponse is recorded reliably is $\lambda_i \sim 950$ nm. This corresponds to the energy of optical ionization of silicon *DX* centers [6].

In GaAs QWs, the shift of the ground state relative to the conduction band of GaAs does not exceed 90 meV (this follows, in particular, from the position of the QW luminescence line, which is found at 1.61 eV at a temperature of 5 K). This shift is insufficient for the formation of *DX* centers directly in GaAs QWs [6]. At the same time, at a growth temperature of 893 K, a certain fraction of silicon atoms diffuse into the $Al_xGa_{1-x}As$ barrier layers, where a *DX* center is stable with respect to shallow donor states, including those located in the GaAs quantum well. The latter is attributable to the fact that the level formed by a *DX* center at $x = 0.27$ is located below the bottom of the GaAs conduction band [6]. Simple estimates demonstrate

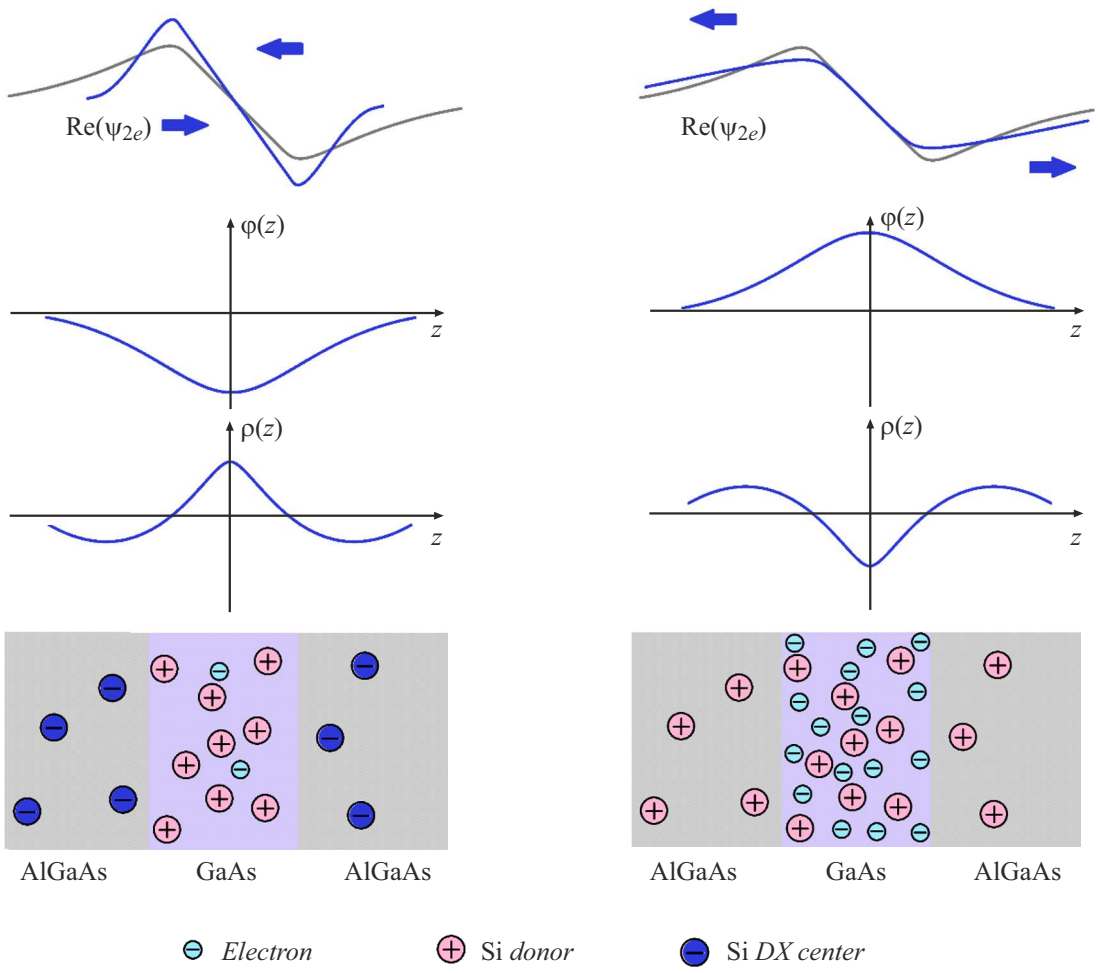

Figure 2. Schematic illustration of the rearrangement of the electronic subsystem of GaAs QWs and wave function ψ_{2e} of the E_{2e} state as a result of photoionization of DX centers located in $Al_xGa_{1-x}As$ layers near GaAs QWs. Charge distribution $\rho(z)$, potential $\varphi(z)$, and the associated changes in the ψ_{2e} wave function before (left) and after (right) the photoionization of DX centers are shown.

that a significant fraction $\alpha \sim 0.2-0.4$ of donors diffuse out of QWs at a growth temperature of 893 K and a growth time of 10 h [7] (this effect is more pronounced for lower QWs, since they remain subjected to a high growth temperature for a longer time). This implies that the number of electrons should increase by a factor of $(1-2\alpha)^{-1} \sim 2-5$ after illumination. This estimate agrees qualitatively with the increase in photocurrent in Figs. 1, *a*, *b*. The above reasoning provides a complete explanation for the changes in the HS transport properties presented in Figs. 1, *a*–*d*. However, the photoresponse rearrangement illustrated in Fig. 1, *e* remains unexpected. Owing to the ionization of a DX center, the number of electrons in the QW increases, which should lead to a proportional increase in the photoconductivity signal intensity. However, curve *2* in Fig. 1, *e* reveals an opposite effect. This behavior indicates a sharp reduction in the light absorption cross section in the $E_{1e}-E_{2e}$ transition and warrants a separate discussion.

The E_{2e} level in GaAs/$Al_xGa_{1-x}As$-based PDDs is located near the edge of the continuous spectrum; therefore, the wave function of an electron on this level should be sensitive to weak additional potential $\varphi(z)$: the attractive nature of $\varphi(z)$ facilitates compression of the state along the z axis that is perpendicular to the QW plane. In turn, repulsive $\varphi(z)$ induces a marked expansion of the state or its transition to a continuous spectrum. This behavior is what distinguishes qualitatively the first excited state E_{2e} from ground state E_{1e} with its wave function localized within the QW and remaining virtually insensitive to additional disturbances. Since the $E_{1e}-E_{2e}$ optical transition probability is determined, among other things, by the overlap of the corresponding wave functions, the QW absorption cross section is also expected to be sensitive to comparatively weak $\varphi(z)$ that blurs or, conversely, localizes the E_{2e} state.

In the studied HS, additional potential $\varphi(z)$ arises inevitably due to electrons and impurities located in the QW or its vicinity and involved in charge exchange. The associated charge distribution $\rho(z)$ rearranges dramatically upon ionization of DX centers located in the vicinity of the QW. In accordance with the Poisson equation, this is accompanied by qualitative changes in $\varphi(z)$. This process

is shown schematically in Fig. 2. When the PE is cooled in the dark, silicon impurities in the vicinity of the QW are negatively charged (the ground state of the system), and the QW has a positive charge due to the loss of a fraction of electrons. In this case, the Coulomb interaction forms an attractive potential for electrons with a minimum at the QW center (see the left part of the diagram in Fig. 2). Following QW irradiation with near-IR light, silicon *DX* centers become ionized, giving up two electrons each to the QW. A metastable state of the system is formed as a result. The drift of electrons contributes to the accumulation of excess negative charge in the QW (see the right part of the diagram in Fig. 2); consequently, a repulsive potential for electrons forms with a maximum at the QW center. Thus, prior to illumination, the E_{2e} state is compressed due to the presence of a negative charge around the QW, and the absorption cross section increases. Following illumination, a positive charge accumulates around the QW, blurring the E_{2e} state. The absorption cross section decreases sharply as a result. Note that the magnitude of the effect described above depends on the specifics of the QW structure (in particular, on the exact depth of the E_{2e} level relative to the bottom of the $Al_xGa_{1-x}As$ conduction band). However, the dissociation of *DX* centers in $Al_xGa_{1-x}As$ layers will invariably reduce the probability of the $E_{1e}-E_{2e}$ transition. The most significant changes are to be expected in the case when the irradiation-induced charge exchange expels E_{2e} into the continuous spectrum.

Thus, a metastable rearrangement of the electronic subsystem caused by irradiation at a wavelength below 950 nm was detected in the GaAs/$Al_xGa_{1-x}As$ HS with silicon-doped QWs. This rearrangement comes down to an increase in the background HS conductivity and a reduction in the photoresponse intensity in the far IR range. It was demonstrated that silicon *DX* centers forming in the vicinity of GaAs/$Al_xGa_{1-x}As$ interfaces and affecting the charge distribution in the QW and its vicinity are instrumental in the observed effect. The detected metastable states arising when the HS is illuminated with near-IR radiation may distort images obtained using standard array PDDs based on GaAs/$Al_xGa_{1-x}As$ HSs, considering that the GaAs substrate is transparent to radiation with a wavelength of ~ 950 nm.

Funding

This study was supported by the Russian Science Foundation (grant No. 19-79-30086).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] F. Jiang, M. Shi, J. Zhou, Y. Bu, J.-P. Ao, X.S. Chen, Adv. Photon. Res., **2** (9), 2000187 (2021). DOI: 10.1002/adpr.202000187

[2] R. Ivanov, D. Visser, S. Smuk, S. Högnadóttir, L. Höglund, L. Bendrot, T. Kohl, L. Žurauskaité, D. Evans, D. Rihtnesberg, D.G. Buldu, A. Smuk, S. Sehlin, S. Almqvist, M. Englund, P. Tinghag, E. Costard, Proc. SPIE, **13046**, 1304615 (2024). DOI: 10.1117/12.3016057

[3] N.A. Kul'chitskii, A.V. Naumov, V.V. Startsev, Fotonika, **16** (1), 22 (2022) (in Russian). DOI: 10.22184/1993-7296.FRos.2022.16.1.22.36

[4] V.S. Krivobok, D.A. Pashkeev, D.A. Litvinov, L.N. Grigor'eva, S.A. Kolosov, Tech. Phys. Lett., **46** (3), 256 (2020). DOI: 10.1134/S1063785020030256.

[5] V.S. Krivobok, A.D. Kondorskiy, D.A. Pashkeev, E.A. Ekimov, A.D. Shabrin, D.A. Litvinov, L.N. Grigoreva, S.A. Kolosov, M.A. Chernopitssky, A.V. Klekovkin, P.A. Forsh, Tech. Phys. Lett., **47**, 388 (2021). DOI: 10.1134/S1063785021040210.

[6] P.M. Mooney, Rad. Eff. Def. Solids, **111-112** (1-2), 281 (1989). DOI: 10.1080/10420158908213003

[7] E.F. Schubert, J.B. Stark, T.H. Chiu, B. Tell, Appl. Phys. Lett., **53** (4), 293 (1988). DOI: 10.1063/1.99917

Translated by D.Safin