Impact of illumination on quantum lifetime in selectively doped GaAs single quantum wells with short-period AlAs/GaAs superlattice barriers

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Impact of illumination on high-mobility dense 2D electron gas in selectively doped single GaAs quantum well with short-period AlAs/GaAs superlattice barriers at $T = 4.2$ K in magnetic fields $B < 2$ T has been studied. It was demonstrated that illumination at low temperatures gives rise to enhancement of electron density, mobility and quantum lifetime in studied heterostructures. The enhancement of quantum lifetime after illumination for single GaAs quantum well with modulated superlattice doping had been explained as consequence of decrease in effective concentration of remote ionized donors.

Keywords: persistent photoconductivity, quantum lifetime, anisotropic mobility, superlattice barriers.

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1. Introduction

Persistent photoconductivity (PPC), which appears in selectively doped GaAs/AlGaAs heterostructures at low temperatures (T) after illumination with visible light, is widely used as a method for changing the concentration (n_e), mobility (μ), and electrons quantum lifetime (τ_q) in such two-dimensional (2D) systems [1–5]. In addition, the PPC phenomenon is used to create one-dimensional lateral superlattices based on high-mobility selectively doped GaAs/AlGaAs [6,7] heterostructures. One of the PPC reasons is the change of the charge state of DX-centers in doped AlGaAs layers AlGaAs after illumination [8,9]. Persistent photoconductivity is undesirable in high-mobility heterostructures intended for the manufacture of field-effect transistors, as it introduces instability into their performance. One of the ways to suppress PPC is to use short-period AlAs/GaAs superlattices as barriers to single GaAs quantum wells [10]. In this case, the sources of free charge carriers are thin δ-doped GaAs layers located in short-period superlattice barriers in which DX-centers do not appear.

Another purpose of using the scheme of remote superlattice doping of single GaAs quantum wells is the realization of 2D electronic systems with both high concentration n_e and mobility μ. In selectively doped GaAs/AlGaAs heterostructures, to suppress the scattering of 2D electron gas at a random potential of ionized donors, the charge transfer area is separated from the doping area by an undoped AlGaAs layer (spacer) [4]. In such a system, high mobility μ is achieved due to a „thick" spacer ($d_S > 50$ nm) at a relatively low density of $n_e \sim 3 \cdot 10^{15}\,\mathrm{m}^{-2}$. To implement high-mobility 2D electron systems with a „thin" spacer ($d_S < 50$ nm) and, accordingly, a high density n_e, it was proposed in the paper [11] to use as barriers to single GaAs quantum wells short period AlAs/GaAs superlattices (Fig. 1). In this case, the suppression of scattering by remote ionized Si donors is achieved not only by separating the areas of doping and transport, but also by the additional screening by X-electrons localized in AlAs layers [11–13].

Superlattice doping of single GaAs quantum wells is used not only to implement high-mobility 2D electronic systems with „thin" spacer [11,12], but also to achieve ultra-high mobility in 2D electronic systems with „thick" spacer [14–16]. In GaAs/AlAs heterostructures with modulated superlattice doping, PPC due to a change in the charge states of DX-centers should not appear [10]. However, it has been found that in selectively doped single GaAs quantum wells with short-period AlAs/GaAs superlattice barriers and a „thin" spacer, illumination increases n_e and μ [17–19], while for structures with a „thick" spacer it significantly increases only τ_q [20] with practically unchanged μ and n_e. This increase τ_q was explained by the redistribution of X-electrons in AlAs layers adjacent to thin δ-doped GaAs layers. However, the effect of illumination on τ_q in single GaAs quantum wells with a „thin" spacer and superlattice doping has not been studied yet.

One of the peculiarities of GaAs/AlAs heterostructures with a „thin" spacer and superlattice doping grown by molecular beam epitaxy on (001) GaAs substrates is the anisotropy of mobility μ [21]. In such structures, the mobility μ_y in the crystallographic direction $[\bar{1}10]$ can exceed the mobility μ_x in the [110] direction by several times [22]. The anisotropy of mobility is due to scattering on the roughness of heterointerfaces, elongated along the $[\bar{1}10]$ direction and arising during the process of heterostructures growth [23,24]. This paper is devoted to studying the effect of illumination on a 2D electron gas with an anisotropic mobility μ in single GaAs quantum wells with „thin" spacer and superlattice doping. It has been established that illumination increases n_e, μ and τ_q in the heterostructures under study. It is shown that the increase in τ_q after illumination is due to a decrease in the effective concentration of remote ionized donors.

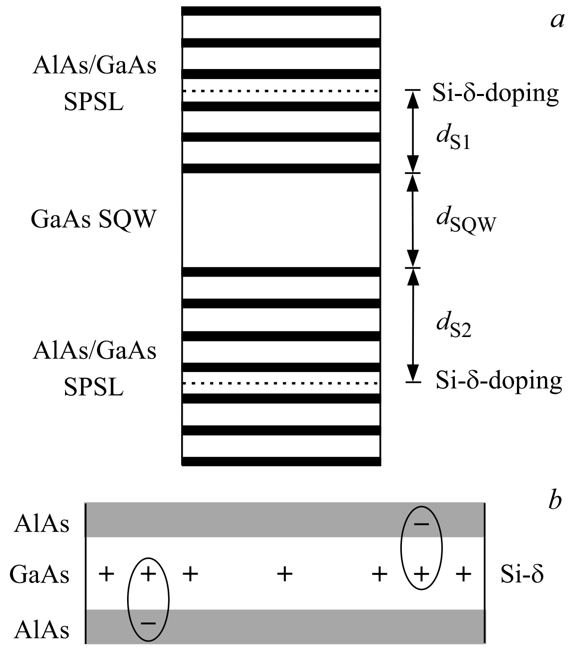

Figure 1. a — schematic view of a single GaAs quantum well (SQW) with short-period AlAs/GaAs superlattices (SPSL) side barriers. b — enlarged view of the δ-section of the doped layer in a narrow GaAs quantum well with adjacent AlAs layers. Ellipses specify compact dipoles formed by positively charged Si donors in the δ-doped GaAs layer and X-electrons in the AlAs layers [13].

2. Quantum lifetime

The traditional method for measuring the quantum lifetime τ_q in a 2D electron gas is based on studying the dependence of the amplitude of the Shubnikov–de Haas (SdH) oscillations on the magnetic field (B) [25–30]. In 2D electron systems with isotropic mobility $\mu = \mu_x = \mu_y$, weak-field SdH oscillations are described by the following relation [28]:

$$\rho^{\mathrm{SdH}} = 4\rho_0 X(T) \exp(-\pi/\omega_c\tau_q) \cos(2\pi\varepsilon_{\mathrm{F}}/\hbar\omega_c - \pi), \quad (1)$$

where ρ^{SdH} — oscillating component of the dependence of dissipative resistance on B, $\rho_0 = \rho_{xx}(B=0) = \rho_{yy}(B=0)$, $X(T) = (2\pi^2 k_{\mathrm{B}}T/\hbar\omega_c)/\sinh(2\pi^2 k_{\mathrm{B}}T/\hbar\omega_c)$, $\omega_c = eB/m^*$, m^* — effective electron mass, ε_{F} — Fermi energy. In a 2D system with anisotropic mobility, when $\mu_x \neq \mu_y$, the normalized amplitude of SdH oscillations will be determined by the following expressions [31]:

$$A_x^{\mathrm{SdH}} = \Delta\rho_x^{\mathrm{SdH}}/\rho_{0xx}X(T) = A_{0x}^{\mathrm{SdH}} \exp(-\pi/\omega_c\tau_{qx}), \quad (2)$$

$$A_y^{\mathrm{SdH}} = \Delta\rho_y^{\mathrm{SdH}}/\rho_{0yy}X(T) = A_{0y}^{\mathrm{SdH}} \exp(-\pi/\omega_c\tau_{qy}), \quad (3)$$

where $\Delta\rho_x^{\mathrm{SdH}}$ and $\Delta\rho_y^{\mathrm{SdH}}$ — the amplitudes of the SdH oscillations measured in the [110] and [$\bar{1}$10] directions, respectively, $\rho_{0xx} = \rho_{xx}(B=0)$, $\rho_{0yy} = \rho_{yy}(B=0)$, $A_{0x}^{\mathrm{SdH}} = A_{0y}^{\mathrm{SdH}} = 4$. According to (2) and (3), in a semilogarithmic scale the dependences of $A_x^{\mathrm{SdH}}(1/B)$ and $A_y^{\mathrm{SdH}}(1/B)$ are linear with slopes determined by the values of τ_{qx} and τ_{qy}, and have starting points $A_x^{\mathrm{SdH}}(1/B=0) = A_y^{\mathrm{SdH}}(1/B=0) = 4$.

In the 2D system under consideration with an anisotropic scattering potential, the quantum lifetime measured using SdH oscillations is an effectively isotropic quantity [31]. This is due to the fact that when an electron moves along cyclotron orbits, the results of individual scattering events are averaged [32].

The value of τ_q in single GaAs quantum wells with short-period AlAs/GaAs superlattice barriers is determined predominantly by small-angle scattering [11,12]. In this case τ_q can be expressed by the relation [33,34]

$$\tau_q \approx \tau_{qR} = (2m^*/\pi\hbar)(k_{\mathrm{F}}d_{\mathrm{R}})/n_{\mathrm{R}}^{\mathrm{eff}}, \quad (4)$$

where $\tau_{q\mathrm{R}}$ — quantum lifetime upon scattering at a random potential of a remote impurity, $k_{\mathrm{F}} = (2\pi n_e)^{1/2}$, $d_{\mathrm{R}} = (d_{\mathrm{S}} + d_{\mathrm{SQW}}/2)$, d_{SQW} — thickness of a single GaAs quantum well, $n_{\mathrm{R}}^{\mathrm{eff}}$ — effective 2D concentration of remote ionized donors. The value of $n_{\mathrm{R}}^{\mathrm{eff}}$ takes into account the change in the degree of influence of the scattering potential of remote donors as a result of the binding of some of them with X-electrons (Fig. 1, b) [13]. The dependence of $n_{\mathrm{R}}^{\mathrm{eff}}$ on n_e in the heterostructures under study is described by the following phenomenological relation [35]:

$$n_{\mathrm{R}}^{\mathrm{eff}} = n_{\mathrm{R0}}^{\mathrm{eff}}/\{\exp[(n_e - a)/b] + 1\} \equiv n_{\mathrm{R0}}^{\mathrm{eff}} f_{ab}(n_e), \quad (5)$$

where $n_{\mathrm{R0}}^{\mathrm{eff}}$, a and b — adjustable parameters. By its nature, f_{ab} — is the fraction of ionized remote donors not associated with X-electrons into compact dipoles.

3. Examined samples and experimental details

The GaAs/AlAs heterostructures under study were grown by molecular beam epitaxy on semi-insulating GaAs (001) substrates. They were single GaAs quantum wells with short period AlAs/GaAs superlattice barriers [11,12]. Two δ-Si layers located at distances d_{S1} and d_{S2} from the upper and lower heterointerfaces of the GaAs quantum well, respectively, served as sources of free electrons. L-shaped Hall bars oriented along the [110] and [$\bar{1}$10] crystallographic directions were fabricated based on the grown heterostructures via optical lithography and liquid etching. The bridges were $100\,\mu$m long and $50\,\mu$m wide. The resistance of the bridges was measured at alternating current $I_{\mathrm{ac}} < 1\,\mu$A with a frequency of $f_{\mathrm{ac}} \sim 0.5$ kHz at a temperature of $T = 4.2$ K in magnetic fields $B < 2$ T. A red LED was used for illumination. The heterostructure parameters are presented in the table.

4. Experimental results and discussion

Figure 2, a shows the experimental dependences $\rho_{xx}(B)$ and $\rho_{yy}(B)$ at $T = 4.2$ K for heterostructure 1 before illumination (curves *1* and *2*) and after illumination (curves *3*

Heterostructure parameters

Structure	d_{SQW}, nm	d_{S}, nm	n_{Si}, $10^{16}\,\mathrm{m}^{-2}$	n_e, $10^{15}\,\mathrm{m}^{-2}$	μ_y, $\mathrm{m}^2/(\mathrm{B}\cdot\mathrm{c})$	μ_x, $\mathrm{m}^2/(\mathrm{B}\cdot\mathrm{c})$	μ_y/μ_x
1	13	29.4	3.2	7.48	124	80.5	1.54
				8.42*	206*	103*	2.0*
2	10	10.8	5	11.5	14.7	9.33	1.58
				14.5*	27.2*	18.6*	1.46*

Note. d_{SQW} — quantum well thickness; $d_{\mathrm{S}} = (d_{\mathrm{S1}} + d_{\mathrm{S2}})/2$ — spacer thickness; n_{Si} — total concentration of remote Si-donors in δ-doped thin GaAs layers; n_e — electron density; μ_x — mobility in direction [110]; μ_y — mobility in direction [$\bar{1}$10]. The asterisk specifies the values obtained after illumination.

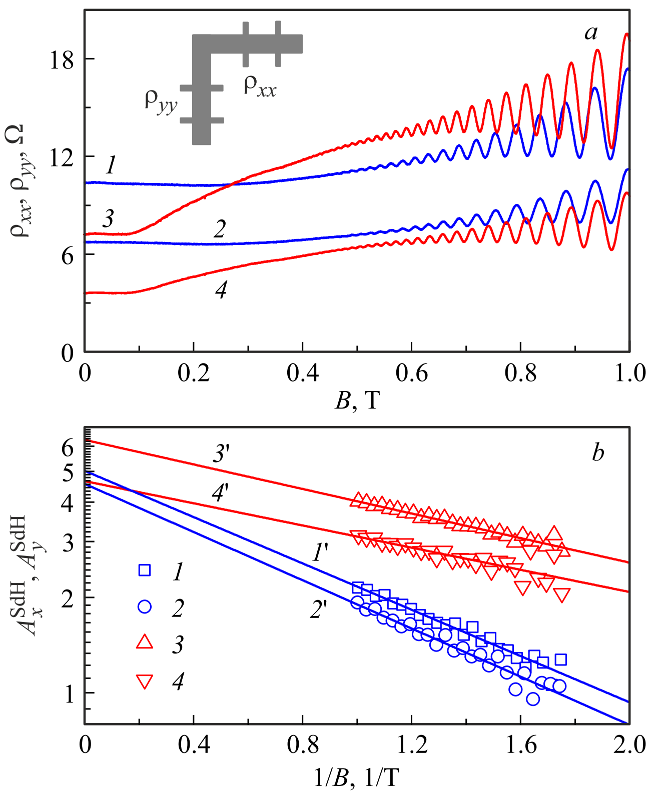

Figure 2. *a* — experimental dependences $\rho_{xx}(B)$ and $\rho_{yy}(B)$ measured on the structure 1 on the *L*-shaped bridge at $T = 4.2\,\mathrm{K}$ before illumination (*1, 2*) and after illumination (*3, 4*). *1, 3* — $\rho_{xx}(B)$; *2, 4* — $\rho_{yy}(B)$. The inset shows the geometry of the *L*-shaped bridge. *b* — dependences of A_x^{SdH} and A_y^{SdH} on $1/B$ before illumination (*1, 2*) and after illumination (*3, 4*). Symbols — experimental data. Solid lines — calculation according to formulas (2) and (3): *1′* — $A_{0x}^{\mathrm{SdH}} = 5.02$, $\tau_{qx} = 1.44\,\mathrm{ps}$; *2′* — $A_{0y}^{\mathrm{SdH}} = 4.68$, $\tau_{qy} = 1.35\,\mathrm{ps}$; *3′* — $A_{0x}^{\mathrm{SdH}} = 6.29$, $\tau_{qx} = 2.72\,\mathrm{ps}$; *4′* — $A_{0y}^{\mathrm{SdH}} = 4.66$, $\tau_{qy} = 3.01\,\mathrm{ps}$.

and *4*). In the area $B > 0.5\,\mathrm{T}$, SdH oscillations are observed. After illumination the period of SdH oscillations has decreased that indicates some increase in n_e. After illumination, the values of ρ_{0x} and ρ_{0y} also decreased, that is due not only to an increase in n_e, but also to an increase in the mobilities of μ_x and μ_y. In addition, illumination led to an increase in the quantum positive magnetoresistance (MR) of the 2D electron gas, which indicates an increase in the quantum lifetime [36,37]. The dependences A_x^{SdH} and A_y^{SdH} on $1/B$ for structure 1 are shown in Fig. 2, *b*. According to formulas (2) and (3), the slopes of these dependences on a semilogarithmic scale are determined by the values τ_{qx} and τ_{qy}. A decrease in the slope after illumination indicates an increase in the quantum lifetime. The observed slight difference between the values of τ_{qx} and τ_{qy} are explained by the limited accuracy of measurements.

Figure 3, *a* shows the experimental dependences $\rho_{xx}(B)$ and $\rho_{yy}(B)$ at $T = 4.2\,\mathrm{K}$ for heterostructure 2 before illumination (curves *1* and *2*) and after illumination (curves *3* and *4*). For this structure, as well as for structure 1, short-term illumination at low temperature leads to an

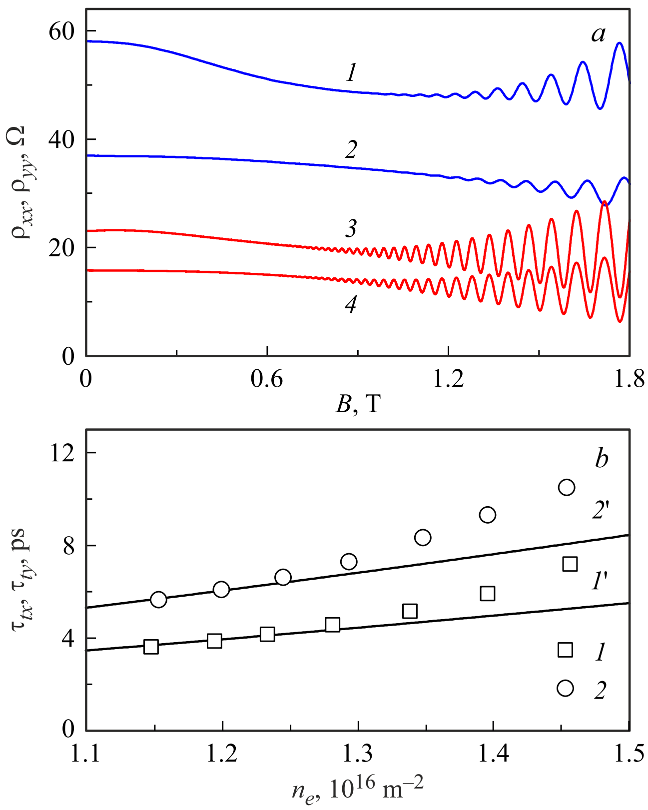

Figure 3. *a* — dependences $\rho_{xx}(B)$ and $\rho_{yy}(B)$ measured on the structure 2 on the *L*-shaped bridge at $T = 4.2\,\mathrm{K}$: *1, 2* — before illumination; *3, 4* — after a short red LED illumination. *b* — $\tau_{tx}(n_e)$ and $\tau_{ty}(n_e)$ dependences. Experimental data: *1* — squares — τ_{tx}; *2* — circles — τ_{ty}. Solid lines — calculation by formulas: *1′* — $\tau_{tx} = C_x n_e^{3/2}$ and *2′* — $\tau_{ty} = C_y n_e^{3/2}$; $C_x = 3.0 \cdot 10^{-36}\,\mathrm{s}\cdot\mathrm{m}^3$, $C_y = 4.6 \cdot 10^{-36}\,\mathrm{s}\cdot\mathrm{m}^3$.

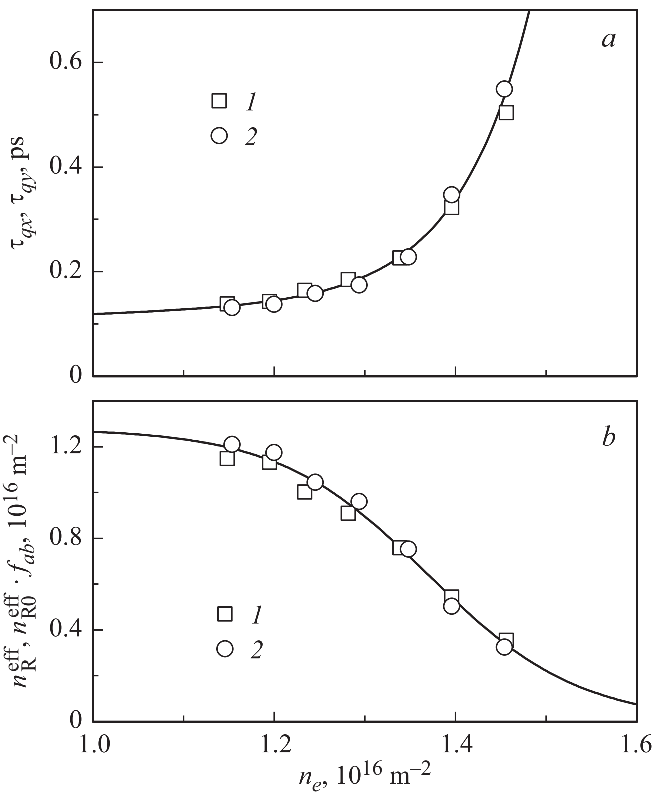

Figure 4. *a* — dependences $\tau_{qx}(n_e)$ and $\tau_{qy}(n_e)$: squares — experimental values τ_{qy}; circles — experimental values τ_{qx}; solid line — calculation by formula (4) for $n_{\mathrm{R}}^{\mathrm{eff}} = n_{\mathrm{R0}}^{\mathrm{eff}} f_{ab}$. *b* — dependences of $n_{\mathrm{R}}^{\mathrm{eff}}$ and $n_{\mathrm{R0}}^{\mathrm{eff}} f_{ab}$ on n_e: squares and circles — $n_{\mathrm{R}}^{\mathrm{eff}}$ values calculated from experimental values of τ_{qx} and τ_{qy}; solid line — $n_{\mathrm{R0}}^{\mathrm{eff}} f_{ab}$ for $n_{\mathrm{R0}}^{\mathrm{eff}} = 1.26 \cdot 10^{16}\,\mathrm{m}^{-2}$, $a = 1.37 \cdot 10^{16}\,\mathrm{m}^{-2}$ and $b = 0.082 \cdot 10^{16}\,\mathrm{m}^{-2}$.

increase in n_e, μ_x and μ_y. However, for structure 2, in contrast to structure 1, the dependences of $\rho_{xx}(B)$ do not exhibit a quantum positive MR, but a classical negative MR [38], which decreases significantly after illumination. Dependences $\tau_{tx}(n_e)$ and $\tau_{ty}(n_e)$ are presented in Fig. 3, *b*. These dependences are not described by the theory [33], which takes into account the change τ_t only with an increase in n_e, since this is due to the change in $n_{\mathrm{R}}^{\mathrm{eff}}$ [35] after illumination. A similar behavior of τ_{tx} and τ_{ty} from n_e is also observed when the density of 2D electron gas is changed using a Schottky gate [12,35].

The experimental dependences $\tau_{qx}(n_e)$ and $\tau_{qy}(n_e)$ for the structure 2 (Fig. 4, *a*) show that the quantum lifetimes for different crystallographic directions are equal to our experimental accuracy, that is consistent with the paper [31]. The experimental data are well described by formula (4), where the effective concentration of positively charged Si donors is calculated by formula (5). The agreement of the experimental dependences $\tau_{qx}(n_e)$ and $\tau_{qy}(n_e)$ with the calculated dependence indicates that the increase in the quantum lifetime of electrons in a single GaAs quantum well after illumination at low-temperature is due to a decrease in $n_{\mathrm{R}}^{\mathrm{eff}}$.

5. Conclusion

In this paper, the effect of short-term illumination was studied at liquid helium temperature on the quantum lifetime of electrons in GaAs/AlAs heterostructures with „thin" spacers — single GaAs quantum wells with modulated superlattice doping. This doping scheme excludes the formation of deep donor states. In this case, almost all Si atoms in thin δ-doped GaAs layers are ionized, but a significant part of the electrons donated by donors populate the X-bands in the adjacent AlAs layers. Recent theoretical studies have shown that positively charged Si donors in thin GaAs layers and X-electrons in adjacent AlAs layers can form compact dipoles [13] and thereby reduce the effective concentration of remote ionized donors $n_{\mathrm{R}}^{\mathrm{eff}}$. In the frame of this consideration, the rate of electron scattering at a random potential of a remote dopant is determined by $n_{\mathrm{R}}^{\mathrm{eff}}$. It was shown that short-term illumination at low temperature leads to a decrease in $n_{\mathrm{R}}^{\mathrm{eff}}$, which is the physical reason for the increase in the quantum lifetime of electrons in the 2D system under study.

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Conflict of interest

The authors declare that they have no conflict of interest.

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