Perspective

Early years of Rashba's scientific career in Ukraine: Size effects and much more

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Professor Emmanuel Rashba worked in Kiev, Ukraine, from 1954 until 1966. An important part of his active scientific life belongs to this period. At that time in Ukraine various physical phenomena in semiconductors were widely investigated, and Rashba took an active part in the development of theory. In addition to well-known results obtained by him that are currently widely cited regarding the symmetry of electron bands, spin states, and the associated effects, Rashba also investigated electron transport in semiconductors under an electric field. Among these studies, a lot of his attention and publications were devoted to the so-called *size effects* in the conductivity of semiconductor microstructures limited by their geometric dimensions due to the sample edges. In this brief article, we have tried to recall Rashba's pioneering works on the size effects and to show their influence on further development of the physics and theory in this interesting and important area of research. In particular, this shows that even then Rashba had a clear understanding that future development of electronics would be directly related to the miniaturization of semiconductor devices, where the influence of physical boundaries and sample edges significantly affect their electrical properties.

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Professor Emmanuel Iosifovich Rashba was working at the Institute of Physics (IP) and the Institute of Semiconductors (IS) in Kiev, Ukraine, from 1954 until 1966, when he moved to the Landau Institute of Theoretical Physics. After that he retained personal and scientific contacts and collaborated with people in Ukraine and came to Kiev regularly, usually once a year, until the collapse of the Soviet Union in 1991. Hence, the early years of his active scientific life took place in the Theoretical Department of the IS, where, after being graduated from the physics faculty of the Kiev State University, we (V.A.K. and V.N.S.) had the fortunate opportunity for direct scientific communication with him; sincere friendliness and accessibility were distinguishing features of Rashba's human character.

At that time, a number of famous scientists such as Professors Nikolay Bogolyubov (Institute of Mathematics, Kiev State University), Solomon Pekar, Kirill Tolpygo, Isaak Dykman, Vadim Lashkaryov (Institute of Semiconductors), Alexander Davydov (Institute of Physics), and others lived and worked in Kiev [1]. Various physical phenomena in semiconductors were widely investigated by the researchers of the IS, in which Rashba took an active part in the development of theory for a wide spectrum of physical effects. Among them were studies related to excitons [2], including the autolocalization problem [3,4] and crystal symmetry [5–7]. Apart from the well-known results obtained by him on the symmetry of spin states that are currently widely cited, a significant part of Rashba's works performed at the IS was devoted to the phenomena of electric transport of the charge carriers in semiconductors under an electric field. Among these studies, much attention was devoted to so-called *size effects* in the conductivity of semiconductor microstructures, where at least one of geometric dimensions is essentially bounded due to the occurrence of sample edges. In particular, this demonstrates that even then Rashba clearly understood future trends in electronics directly related to miniaturization of perspective semiconductor devices. Nowadays, these ideas have renewed interest in the size effects in application to modern nanostructures of various low-dimensional semiconductor materials. In this brief article, we have tried to recall Rashba's earliest works on the size effects and demonstrate their impact on further development of theory in this interesting area.

Further, we would like to point out a few of the size effects which are closely associated with Rashba's name. The physical reason for different size effects to become possible is the peculiar property of semiconductors under an electric field to exhibit a hierarchy of electronic relaxation times τ, representing the rates of relaxation of an electronic system to the equilibrium state. In many cases, the time τ_p of an electron's momentum relaxation is the shortest characteristic time (especially at low temperatures) in the existing time hierarchy; this results in a similar hierarchy for characteristic diffusion lengths, $L = \sqrt{D\tau}$, associated with these (long) relaxation times, $\tau \gg \tau_p$.

The transverse size effects arise when the device dimension d in a transverse direction relative to the flowing current approaches one of the characteristic diffusion lengths: the electron-hole recombination length L_r in bipolar materials, the intervalley length L_{iv} in multivalley semiconductors, the

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cooling length L_c of the carriers heated with an electric field, etc. Therewith, the following inequalities are realized: $L_r \gg L_{iv} \gg L_c \gg L_p$. That is, the largest characteristic length is associated with the longest relaxation time. When the transverse sample dimension d is reduced, these characteristic lengths become sequentially comparable with d and, therefore, the size effect begins to manifest itself in the phenomena described by the respective diffusion length L. A theoretical description of the considered size effects is restricted by using an essentially classical approach for the carriers and drift-diffusion carrier transport ($L \gg \lambda$, where λ is the de Broglie wavelength). Below, we briefly describe a few examples of size effects studied under direct impact of Rashba's works [8–10], which are addressed below in order of decreasing characteristic diffusion lengths.

I. ELECTRON-HOLE RECOMBINATION LENGTH L_r

The theory and experimental observation of transverse redistributions of the electrons and holes in anisotropic intrinsic semiconductor microstructures (electric pinch effect) were reported in Refs. [11,12]. The analogous phenomena may arise in the case of bipolar conductivity in isotropic semiconductors where effective transport anisotropy is induced by applied crossed electric and magnetic fields. Later, size effect on the electron-hole recombination length was studied in a number of narrow-gap semiconductors and found sensor and emitter applications. Nowadays, in Ref. [13], the transverse redistributions of electrons and holes have been investigated in intrinsic graphene ribbons of the width $d \sim L_r$ caused by the influence of crossed electric **E** field and magnetic **H** field. The geometry and main physical assumptions of the considered problem follow the ideas of the above-cited works. The electric and magnetic fields are applied to a single-layer graphene ribbon in the xy plane, along the x and z axes, respectively. The magnetic field is classically strong; i.e., it does not lead to the Landau quantization of the electron and hole energy spectrum. The ribbon length L_x is the longest sample dimension allowing a one-dimensional treatment of the problem, with the inhomogeneity along the y axis alone. The problem was solved using drift-diffusion equations supplemented with boundary conditions at the ribbon edges in terms of phenomenological velocity of surface electron-hole recombination. It was shown that the transverse exclusion of carriers from the bulk to one of the sample edges resulted in an accumulation layer of the width of L_r. The estimates for intrinsic graphene at a temperature of 150 K and a magnetic field of 1.5 kG demonstrated that population inversion could be achieved in the accumulation mode. This potentially allows amplification or generation of electromagnetic radiation in a certain bandwidth around the frequency of about 1 THz.

II. INTERVALLEY LENGTH L_{iv}

Studying the electron energy bands in Ge and Si, Rashba noted the existence of a few groups of carriers (a few valleys populated by the carriers) with a relatively long time of the intergroup (intervalley) transitions ($\tau_{iv} \gg \tau_p$) which resulted from the considerable separation of the valleys in the **k** space. In such cases under nonequilibrium conditions, large macroscopic effects in redistribution of the carriers between such relatively independent groups can be expected.

Electrically induced separation of free electrons of different valleys in bulk multivalley semiconductor structures with restricted geometry was first proposed by Rashba in 1965 [8]. Manifestation of spatial separation of the electrons of different valleys was observed in experimental works with thin Si samples [10]. The important feature of this effect is that the transverse redistributions of the valley electron density can appear under the strong (but *nonheating*) electric field in the form of domains [9], that is, the well-resolved spatial regions characterized by the domain plateau and the wall, with characteristic lengths of the order of $L_{iv}E$ and L_{iv}/E, respectively, where $L_{iv} = (D\tau_{iv})^{1/2}$ (D is the diffusion coefficient, τ_{iv} is the intervalley time). The size effect under the *heating* electric field was considered in Ref. [14]. The domain details depend on the multivalley band model and the carrier transport anisotropy.

Currently, the Rashba size effect remains relevant for the rapidly developing field of valleytronics (valley-dependent electronics and optoelectronics based on the exploitation of the valley degree of freedom). In Refs. [15–19], analogous effects have been investigated in contemporary nanostructures including two-dimensional (2D) multivalley materials as well as many-layer nanostructures with electrostatically coupled anisotropic nanolayers. Specifically, semiconductor nanosystems have been analyzed with equivalent anisotropic valleys (n-Si, n-AlAs, etc.) [17] as well as 2D Dirac materials without inversion symmetry and with normally isotropic valleys (gapped graphene, transition-metal dichalcogenides, etc.) [18]. In the later case, electrical anisotropy is inherent in the Berry-phase supported topological transport [20]. Also, van der Waals (vdW) heterostructures made from atomically thin charge-coupled monolayers of different anisotropies have been considered [19] where the charged domains are formed in each monolayer of a multilayer vdW-ribbon heterostructure.

Note, Rashba's idea about spatial separation of charge carriers with different electrical properties also found its development in the spin-Hall effect [21–23] – separation of electron fluxes with different spin orientations. In strong electric fields, both the valley-Hall and spin-Hall effects can lead to the formation of spin- and valley-polarized spatial Rashba-like domains.

It is known that in several groups of carriers with different properties, random exchange of the carriers between these groups initiates the electron density fluctuations (the intervalley fluctuations) and the current noise. Theoretical studies [24] of the intervalley fluctuations in submicrometer active layers, for which the boundaries and size effects are relevant, have demonstrated that under considered size effects the intensity of low-frequency intervalley fluctuations can be controlled and suppressed in semiconductor structures of submicrometer sizes.

III. HOT-ELECTRON COOLING LENGTH L_c

The considered electronic system is characterized by the times τ_p, τ_ε, and τ_{ee}, where τ_{ee} is the electron-electron collision time. If τ_p is governed by quasielastic scattering, then

one may assume $\tau_p \ll \tau_\varepsilon, \tau_{ee}$. If in addition $\tau_{ee} \ll \tau_\varepsilon$, an electron temperature $T_e(y)$ is established in the electron gas. The temperature $T_e(y)$ is determined by the equation for the electronic thermal conductivity. It is established in a distance of the order of $L_{ee} = (D\tau_{ee})^{1/2}$ and relaxes in a cooling length $L_c = (D\tau_\varepsilon)^{1/2}$. In narrow conducting channels of the width $d \lesssim L_c$, the occurrence of surface-energy relaxation at the edges reduces considerably the electron heating by the applied electric field and alters the conductivity, so that the conductivity becomes size dependent [25–27]. Based on these results, the fluctuations of the spatially inhomogeneous hot-electron gas have theoretically been investigated with regard to the size effect related to the characteristic cooling length L_c [28]. The spectral densities of fluctuations of the electron temperature and current have been shown to become dependent on the channel width. For the channels with $d < L_c$, the suppression of fluctuations arises in the range of fluctuation frequencies $\omega \ll \tau_\varepsilon^{-1}$, where τ_ε is the electron-energy relaxation time.

Summarizing, we have highlighted Rashba's ideas and works generated during his life and research in Ukraine. Being an outstanding physicist, Professor E. I. Rashba will also be remembered as a great teacher, who left behind a whole generation of worthy researchers.

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DATA AVAILABILITY

No data were created or analyzed in this study.

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