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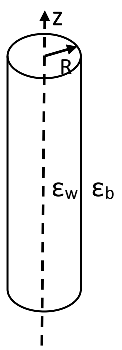
K.H. AHARONYAN, N.B. MARGARYAN

DIELECTRIC CONFINEMENT AFFECTED QUANTUM SCREENING OF QUASI ONE DIMENSIONAL ELECTRON GAS IN SEMICONDUCTOR QUANTUM WIRES

A formalism of the Thomas-Fermi method has been applied for studying the screening effect in the semiconductor quantum wire embedded in a barrier environment. The analytical expressions for the 3D screened interaction potential and Q1D screening length are derived for the first time. With the account of strongly low dielectric properties of the barrier environment, an applicability of the Q1D interaction potential of the confined charges has been revealed.

Keywords: quantum wire, screening effect, interaction potential.

The depth and wide scope of the physics of low-dimensional structures is due to strong correlations, and are mainly caused by the weak screening of the Coulomb interaction in these systems. The strength and the further enhancement of the Coulomb interaction potential results in the lowering of the system dimensionality. In a 3D system, a screened potential decays exponentially in the real space. In the pure 2D structures, the real–space statically screened potential in the long-wavelength limit possess the 2D Coulomb law spatial dependence for intermediate distances and power law spatial dependence for large distances, respectively. It is assumed that the tendency of the weakening of the Coulomb interaction should go on more strong by for the transition from quantum wells (QW) to quantum wires (QWR).



The physical concept, that dielectric screening would be insufficient to reduce the Coulomb repulsion between charge carriers in 1D case started from the work of Kuper [1] and is reinvestigated in [2] by Davis, where the screened point charge Coulomb potential expression inside and outside the *conducting* 1D single-wire was obtained in the Tomas-Fermi approximation (TFA). Lee and Spector [3], Reyes et al. [4] derived the dielectric function of 1D EG and asymptotic forms of the pure 1D screened Coulomb potential of the point charge in *semiconductor* QWR embedded in a dielectric barrier environment.

A realistic semiconductor QWR either can be freestanding or surrounded with a barrier environment appropriate to device application. In this sense, for Coulomb center (excitons, impurities) - based devices, use of the low dielectric constant barrier environment of semiconductor QWR (lower than semiconductor dielectric constant) is favorable as it enhances the Coulomb interaction inside the QWR (dielectric confinement effect (DC)). In this work, a consistent theory of dielectric screening is developed incorporating the DC effect. For that purpose ,we resort a fully 3D calculation of the screened potential in the QWR exhibited within the TFA framework. Our treatment differs from that derived in [1-4], where it is assumed that the Q1D EG has an infinite homogeneous background having dielectric constant the same as the semiconductor.

Let us consider an infinitely long semiconductor cylindrical QWR (CQWR) of a radius R filled by the active material with the dielectric constant ε_w and immersed in a dielectric barrier environment with the dielectric constant ε_b in the polar coordinates (ρ,φ,z), where the z axis coincides with the CQWR axis. The interaction potential $V_S(\rho,\, z)=e\Phi_S(\rho,\, z)$ of charges *–e* and *e* to be located at (0, 0) and (ρ,z) respectively, is related to the induced charge 3D density by Poisson's equation

$$\nabla^2\Phi_S(\rho,z)=-\left(4\pi e/\varepsilon_w\right)\left[\delta(\rho)\delta(z)-\Delta n_V(\rho,z)\right], \tag{1}$$

where $\Delta n_V(\rho,z)=n_V[\mu_0+e\Phi_S(\rho,z)-n_V(\mu_0)]$ is the variation of the charge density of Q1D electrons, μ_0 is the chemical potential in the absence of the external field. Due to the cylindrical and reflection symmetry of the problem, Eq.(1) becomes independent of the coordinate φ and is separable in ρ and z coordinates.

Within the framework of the TFA method, it is believed that the Q1D EG is in its lowest quantum state, i.e. only one energy size-quantized subband is filled. In turn, the spatial variation of the screened potential is small over distances comparable to the electron de Broglie wavelength. The latter supposes to be larger than the CQWR radius R , i.e. the long wave condition kR<1 holds, where $\vec{k}$ is the electron 2D wave vector. In the assumptions that the externally applied charge *–e* produces only a linear response in Q1D EG, for large enough distances when $e\Phi_S << \mu_0$ we may obtain the variation $\Delta n_V(\rho,z)$ as $\Delta n_V(\rho,z)=(\partial n_V/\partial\mu_0)e\Phi_S(\rho,z)$.

Substituting the latter in the first equation of system (1) and expressing the screening potential $V_S(\rho,z)$ in Fourier components as $V_S(\rho,q)$ we will have

$$\left(\frac{\partial^2}{\partial\rho^2}+\frac{1}{\rho}\frac{\partial}{\partial\rho}\right)V_S(\rho,q)-\left[q^2+\frac{4\pi e^2}{\varepsilon_w}\frac{\partial n_V(\rho,z)}{\partial\rho}\right]V_S(\rho,q)=-\frac{4\pi e^2}{\varepsilon_S}\delta(\rho),\quad \rho\le R\quad , \tag{2}$$

where $q=k-k'$. The characteristic size of the spatial change of the quantity $\partial n_V(\rho,z)/\partial\mu_0$ is significantly in the order of the radius R . Replacing the latter by the averaged in the z axis by the normal plane expression

$\partial \bar{n}/\partial \mu_0 = S^{-1}\int_0^R \partial n_L/\partial \mu_0 \left|\psi_e(\rho,\varphi)\right|^2 \rho d\rho d\varphi$, we can obtain an equation independent of the variable ρ coefficient $\tilde{q}^2 = q^2 + q_L^2$, where $q_L = \left[(4\pi e^2/\varepsilon_w)(\partial \bar{n}/\partial \mu_0)\right]^{1/2}$ is the averaged TFA screening parameter, n_L is the linear charge density, $\psi_e(\rho,\varphi)$ is the electron single-particle wave function in the CQWR axis normal plane, $S = \pi R^2$. As we can see, the characteristic spatial distance in CQWR that the solution of the Eq. (2) changes appreciably is order of the $\tilde{q}^{-1}$. If the condition $\tilde{q}R < 1$ holds, then $V_S(\rho,q)$ approximately coincides with the solution of Eq.(2) with the coefficient $\tilde{q}^2 = q^2 + q_L^2$ and thus we will take into account just the latter equation. The general solution with axial and reflection symmetry in the origin of Eq.(2) with the $\tilde{q}^2 = q^2 + q_L^2$ inside the CQWR is [2,3]

$$V_S(\rho,z) = \int_0^\infty \cos qz\left[A(q)\, I_0(\tilde{q}\rho) + B(q)\, K_0(\tilde{q}\rho)\right]dq, \qquad (3)$$

where I(x) and K(x) are modified Bessel functions, A(q) and B(q) coefficients are determined by applying the boundary conditions. They are arbitrary functions of 1D wave vector q and for each value of that Eq.(2) with the $\tilde{q}^2 = q^2 + q_L^2$ has a linearly independent solution. These coefficients have been determined by the requirement of the limiting asymptotic expressions of the electrostatic potential $V_S(\rho,z)$ both at the origin and infinity whereas applying as well two standard Maxwell boundary conditions at the semiconductor CQWR surface. For the sought 3D interaction screened potential of semiconductor CQWR embedded in a dielectric barrier environment with the dielectric constants ε_w and ε_b ,we respectively obtain

$$V_S(\rho,z) = -\frac{2e^2}{\pi\varepsilon_w}\int_0^\infty \cos qz\left[K_0(\tilde{q}\rho) + \frac{I_0(\tilde{q}\rho)\left[\varepsilon_r\tilde{q}K_0(qR)K_1(\tilde{q}R) - qK_0(\tilde{q}R)K_1(qR)\right]}{\varepsilon_r\tilde{q}K_0(qR)I_1(\tilde{q}R) + qK_1(qR)I_0(\tilde{q}R)}\right]dq. \qquad (4)$$

Now we will obtain the CQWR Q1D interaction screened potential analytic expressions taking into account the DC effect. In order to get a general qualitative insight into the “Coulomb interaction engineering” possibilities of the DC effect the following consideration will be presented for a simplest but a most interesting case: $\varepsilon_r = \varepsilon_w/\varepsilon_b >> 1$. Thus, a strong contrast between dielectric constants ε_w and ε_b is accepted and it is assumed that the radius of the quantum wire is small compared with the Bohr radius a_0 for bulk samples. The strong confinement condition $a_0 >> R$ for the distances along the wire axis $|z| >> R$ is appropriate to the long wave region $q << R^{-1}$ in accordance with TFA. This allows to apply a geometrical adiabatic method and for that a 3D Coulomb screened potential admits a Q1D form. At the same time, in the previous section, the condition $\tilde{q}R << 1$ has been used meaning that the typical spatial change of the screened potential energy's Fourier-component is larger than the CQWR radius. The latter will be realized when the following two conditions are simultaneously fulfilled $qR \; << 1, q_L R << 1$.

According to the strong confinement condition $a_0 >> R$ in QWR, at intercharge distances $|z| >> R$ in the integral after Exp.(4), the wave vectors are effective, which is related to the last expressions. In that case the screened potential does not depend on ρ and takes the Q1D form

$$V_S^{Q1D}(z) = -\frac{e^2}{\varepsilon_w}\frac{e^{-q_S|z|}}{|z|} - \frac{2e^2}{\pi\varepsilon_w}\int_0^\infty \cos qz \frac{\varepsilon_r \ln(qR)^{-1} - \ln(\tilde{q}R)^{-1}}{\varepsilon_r (qR)^2 \ln(qR)^{-1} + 1} dq \,. \quad (5)$$

In view of the long wave ($q << R^{-1}$) and the DC effect ($\varepsilon_r = \varepsilon_w / \varepsilon_b$ >> 1) conditions, in Exp.(5), the main contribution goes on just from the inhomogeneous polarization related second term. In Exp.(5), there exist two distinct 1D effective wave vector ranges for the moderate small and very small q vectors appropriate to the long wave region, such as: $\varepsilon_r (qR)^2 \ln(qR)^{-1} \geq 1$ and $\varepsilon_r (qR)^2 \ln(qR)^{-1} << 1$, that the Q1D screened interaction potential $V_S^{Q1D}(z)$ takes the asymptotic analytic forms. As it follows, at intermediate distances z corresponds to the criteria: $|z| >> R$ and $\varepsilon_r (R/z)^2 \ln |z|/R \geq 1$, which are appropriate to the "moderately" thick cylindrical wires, the screened potential $V_S(z)$ takes the form

$$V_{S\,i}^{Q1D}(z) = -\left(e^2 / \varepsilon_w \tilde{q}_L R^2\right) e^{-\tilde{q}_L z} \,. \quad (6)$$

Where $\tilde{q}_L = \left[\tilde{q}_L^2 + (2/R^2 \varepsilon_r \ln \varepsilon_r)\right]^{1/2}$ is the DC effect influenced effective TFA screening parameter.

In the case of very large distances z corresponds to the criteria $|z| >> R$ and $\varepsilon_r (R/z)^2 \ln |z|/R << 1$ the screened potential $V_S(z)$ takes the form

$$V_{S\,i\,i}^{Q1D}(z) = -e^2 / \varepsilon_b \sqrt{z^2 + R^2} \quad , \quad (7)$$

which is appropriate to the extremely thin wires.

As can be seen from the Exp.(6), the DC affected screening potential deviates from the 3D and pure 1D cases, takes the Q1D form and strongly enhances with the reducing of the CQWR thickness. At the same time, the Q1D screening effect emerges for the intercharge distances only which is appropriate to the “moderately” thick quantum wires. The screened potential $V_{S\,i}^{Q1D}(z)$, in this case, strongly depends on the effective TFA screening parameter $\tilde{q}_L$ and is enhanced due to the presence of the small parameter $\tilde{q}_L R$ << 1 in denominator. In turn, $V_{S\,i}^{Q1D}(z)$ is exponentially weak enough outside the spatial region with the linear size of $z_0 = \tilde{q}_L^{-1}$, where z_0 is believed to be the Q1D screening radius in CQWR.

As related to the thin enough quantum wires, the general formula for the screened interaction potential $V_{S\,i\,i}^{Q1D}(z)$ reduces to the 1D Coulomb dependence ~ $|z|^{-1}$ with the surrounding barrier environment small dielectric constant. Thus, in the case of thin enough quantum wires, the Q1D screening effect does not wholly emerge. That is fairly natural, since in the Q1D and 1D systems for the large enough intercharge 1D distances z, the predominant part of the electric field lines extend outside the free carrier confinement region. As a result, the free carriers cannot effectively screen the Coulomb field between any two charges inside the thin enough quantum wire.

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Կ.Հ. ԱՀԱՐՈՆՅԱՆ, Ն.Բ. ՄԱՐԳԱՐՅԱՆ

ԴԻԷԼԵԿՏՐԻԿԱԿԱՆ ՍԱՀՄԱՆԱՓԱԿՄԱՆ ԱԶԴԵՑՈՒԹՅՈՒՆԸ ՔՎԱԶԻՄԻԱՉԱՓ ԷԼԵԿՏՐՈՆԱՅԻՆ ԳԱԶՈՎ ՊԱՅՄԱՆԱՎՈՐՎԱԾ ԷԿՐԱՆԱՎՈՐՄԱՆ ՎՐԱ ԿԻՍԱՀԱՂՈՐԴՉԱՅԻՆ ՔՎԱՆՏԱՅԻՆ ԼԱՐԵՐՈՒՄ

Թոմաս-Ֆերմիի մեթոդի կիրառմամբ քննարկված է էկրանավորման երևույթը արգելքային միջավայր ներառված կիսահաղորդչային քվանտային լարերում: Դիէլեկտրական սահմանափակման երևույթի հաշվառումով առաջին անգամ ստացված են ինչպես էկրանավորման եռաչափ փոխազդեցության պոտենցիալի, այնպես էլ քվազիմիաչափ էկրանավորման փոխազդեցության պոտենցիալի և էկրանավորման երկարության բանաձևերը:

Առանցքային բառեր. քվանտային լար, էկրանավորում, փոխազդեցության պոտենցիալ:

К.Г. АГАРОНЯН, Н.Б. МАРГАРЯН

ВЛИЯНИЕ ДИЭЛЕКТРИЧЕСКОГО ОГРАНИЧЕНИЯ НА ЭКРАНИРОВАНИЕ С КВАЗИОДНОМЕРНЫМ ЭЛЕКТРОННЫМ ГАЗОМ В ПОЛУПРОВОДНИКОВЫХ КВАНТОВЫХ НИТЯХ

С применением метода Томаса-Ферми исследовано явление экранирования в полупроводниковых квантовых нитях, вкрапленных в барьерную среду. С учетом явления диэлектрического ограничения впервые получены выражения как для потенциала трехмерного экранированного взаимодействия, так и для квазиодномерного потенциала взаимодействия и длины экранирования.

Ключевые слова: квантовая нить, экранирование, потенциал взаимодействия.

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Д.Б. АЙРАПЕТЯН, Ж.Р. ПАНОСЯН, Ю.Ж. ТУЛЕУШЕВ

ИССЛЕДОВАНИЕ КОМБИНАЦИОННОГО РАССЕЯНИЯ ИЗЛУЧЕНИЯ ТОНКОПЛЕНОЧНЫМ АМОРФНЫМ КРЕМНИЕМ, ЛЕГИРОВАННЫМ НАНОЧАСТИЦАМИ СЕРЕБРА

Исследованы особенности процесса одновременного магнетронногонапыления на подложку поликристаллического кремния и серебра. Получены покрытия из аморфного кремния с распределенными в нем наночастицами серебра, а также электронно-микроскопические и атомно-силовые снимки этих покрытий. Исследования комбинационного рассеяния спектров полученных пленок показали усиление рассеяния колебательных мод пленок аморфного кремния с наночастицами серебра.

Ключевые слова: аморфный кремний, наночастицы серебра, комбинационное рассеяние.

Введение. В последние годы интенсивно разрабатываются тонкопленочные солнечные элементы (СЭ). Традиционные монокристаллические кремниевые подложки заменены здесь пленками аморфного кремния толщиной 0,5…1 *мкм*