А.Ж. ХАЧАТРЯН

ВОЗДУХОНАГРЕВАТЕЛЬНАЯ УСТАНОВКА, АККУМУЛИРУЮЩАЯ ЭНЕРГИЮ СОЛНЦА

Предлагаемая в работе установка относится к направлению солнечной энергетики в области альтернативной энергетики. Являясь аккумулирующей установкой для энергии Солнца, она позволяет получать большие объёмы теплого воздуха в течение дня вплоть до глубокой ночи. Представленная установка осуществляет преобразование накопленной в течение дня энергии Солнца в тепловую энергию воздушного потока.

Ключевые слова: солнечная энергетика, накопитель тепла, воздухонагреватель.

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AN AIR-HEATING FACILITY ACCUMULATING THE SOLAR ENERGY

The proposed facility is referred to the direction of Solar energy in the alternative energy area. Being an accumulation facility for the Solar energy, it allows to receive large volumes of warm air throughout the day until late at night. The introduced unit realizes the conversion of the Solar energy accumulated during the day in to the thermal energy of an air flow.

Keywords: Solar energy, heat accumulator, air heater.

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SCREENED IMPURITY ENERGY OF QUANTUM WELL WITH THE HIGH-k TYPE DIELECTRIC CONTRAST

Quantum well / high-κ type barrier dielectric mismatch related problem is elaborated from the first principles. An influence of the Debye-Hückel type potential analytical features on the screened impurity binding energy is considered for the first time. Inclusive numerical analysis of both *high-κ barrier/quantum well/high-κ barrier* and *low-κ barrier/quantum well/high-κ barrier* two-dimensional structures on the basis of InSb/HfO_2 heterointerface is investigated.

Keywords: quantum well, impurity, high – k type dielectric contrast.

Since the scaling of optoelectronic devices is currently reaching its own available physical and best possible limits, the semiconductor quantum well (QW) channels with highly mobile carriers and dielectric gate layers with sub-nanometer equivalent thickness acquire the decisive importance in semiconductor technology. At present, these challenges lead to the justified utilization of the III-V group semiconductor and high-k dielectric materials correspondingly as QW and barrier media in the QW nanosystems [1]. Along with this a question of impurity states influenced by image charges distribution in the semiconductor high mobility QW system on the basis of high-κ gate dielectrics arises [2]. So a unique opportunity in these nanostructures emerges that by mutual adjusting both the QW width d and the dielectric constants ratio $\varepsilon_{r\,1\,(2)} = \varepsilon_w / \varepsilon_{b1}\ (\varepsilon_{b2})$ of the QW and the surrounding barrier media to rule the impurity pair interaction intensity and thus impurity energies [2, 3]. At the same time, the optical and transport phenomena may become more specific due to the multi-body effect in the form of screening the polarization field around the background impurity center by the Q2D electron gas (Q2D EG). In 3D samples the screened Coulomb interaction is characterized by Debye-Hückel type short-range potential because of the exponential functional law decrease in the real space. As for the Q2D (2D) samples, the physical conditions here become much more complicated since the screening effect influence weakens and the screened Coulomb interaction demonstrates genuinely long-range spatial behavior [4, 5]. As shown in Ref.[4] and subsequently in Refs.[5], at the possible interplay between $\varepsilon_{r1(2)}$ and QW width d values in the case of $\varepsilon_r \gg 1$, corresponding to the **low-κ barrier/QW/low-κ barrier**($\varepsilon_w \gg \varepsilon_b = \varepsilon_{b1} = \varepsilon_{b2}$) dielectric mismatch type Q2D structures (below we denote as ***ll-k* type** QW structure), $V_S\ (\rho)$ for the intermediate or moderately large 2D distances takes either logarithmical or exponential functional dependencies. A recovery of the 2D screening radius quantity ρ_s in $V_S(\rho)$ has been received as well in the case of dielectrically inhomogeneous QW structures characterized by criteria $\varepsilon_w \gg \varepsilon_{b1},\ \varepsilon_w \sim \varepsilon_{b2}$ [6].

Very recently, a consistency of the developed in [5] theoretical model with the logarithmical potential is established in Ref. [7], where in the 2D methylammonium lead halide perovskite ($MAPbBr_3$) nano-sheets experimentally clearly has been confirmed that the plasma excitation density can significantly affect the final screened exciton binding energy and the position of the excitonic resonance.

Thus, it can be asserted that in the QW heterostructures subject to different types of dielectric mismatch, a study of the Q2D screening properties in the spatial region characterized by moderately large 2D distances gives diverse and characteristic data on the Coulomb screened interaction problem and becomes more applicable and receptive both from scientific and practical points of view.

What about the **QW/high-κ barrier** dielectric mismatch type topic with the condition of $\varepsilon_{r1(2)} < 1$, corresponding to **high-κ barrier/QW/high-κ barrier** type QW structures (below we denote as ***hh-k* type** QW structure), a comprehensive analytical consideration of the Q2D screened potential problem taking into account a correlation between the values of the parameters d and ε_r is not currently developed yet. In Ref.4 the author has limited to deducing the screened interaction potential energy's Fourier-component at the extremely small electron 2D wave vectors in the long wave asymptotic limit (correspondingly for the asymptotically large 2D distances and, at the same time, under very small dielectric constants ratio values ($\varepsilon_r = \varepsilon_{r1} = \varepsilon_{r2} << 1$).

Consider a semiconductor QW structure with the dielectric constant ε_w neighboured with surrounding barrier media having the dielectric constants $\varepsilon_{b\ 1,\ 2}$ and containing Q2D EG with the average surface density n_S. In discussed model only the n-type Q2D charged channel contributes to the screening of the charges. Here, for such a QW heterostructure, we start from the criteria relating both to the strong **spatial confinement** and to the **high κ-dielectric barrier** effects characterized by conditions $a_0 >> d$ and $\varepsilon_r = \varepsilon_w / \varepsilon_b < 1$, respectively, where $a_0 = \varepsilon_w \hbar^2 / m_e e^2$ is the Bohr radius in the bulk samples, m_e – is the electron effective mass. Necessarily we assume also that the QW thickness d is small compared with the Debye radius for bulk samples as $r_D >> d$. The Fourier-component $\varphi_s(k, z, z_0)$ of the screened interaction $V_S(\rho, z, z_0)$ between the charges $-e$ and e located at the points (0, z_0) and (ρ, z) in the QW region ($-d/2 \le z \le d/2$) is [6].

$$\varphi_S(k,z,z_0) = -\frac{4\pi e^2}{\varepsilon_w \tilde{k}} \frac{\cosh[\,\tilde{k}(d/2 - z) + \eta\,]\cosh[\,\tilde{k}(d/2 + z_0) + \eta\,]}{\sinh[\,\tilde{k}d + 2\eta\,]} \qquad (1)$$

where $\eta = 0.5 \ln |(\varepsilon_w \tilde{k} + \varepsilon_b k)/(\varepsilon_w \tilde{k} - \varepsilon_b k)|$, $\tilde{k} = (k^2 + \rho_s^2)^{1/2}$, $\rho_s = (2q_s/d)^{1/2}$, k - is the 2D electron wave vector, ρ – is the planar coordinate, the z axis is normal to the QW plane, q_s – is the 2D screening parameter (more see [4-6]) .

With the relations $a_0 >> d$ and $r_D >> d$ there exists in the interval effective wave vectors $\tilde{k} << 1/d$ that the typical spatial change of $\varphi_s(k, z, z_0)$ is large enough than d. Since $\tilde{k}d << 1$ the long wave related wave vector k values can be chosen at the condition $\varepsilon_r < 1$ for which the relationships $2\eta > 1 >> \tilde{k}d$ may take place. The latter goes to

$$1/d >> k > \rho_s^{-1}\left(\left((e^2+1)/(e^2-1)\varepsilon_r\right)^2 - 1\right)^{-1/2} \qquad (2)$$

for that the screened impurity interaction potential takes the following Q2D form

$$V_S^{hh-k}(\rho) = -(e^2/\varepsilon_w)[\exp(-\rho/\rho_s)]/\rho\,, \qquad (3)$$

where $e = 2.71..$- is the natural number.

As it follows, the Q2D screening potential after Exp. (5) for the moderately large in-plane distances (~ ρ_s) is characterized by 2D Debye-Hückel type spatial dependence and thus exponentially decays outside the circle by radius ρ_s. This leads to the restoration of the 2D screening radius ρ_s as such in the Q2D system and therefore a 3D screened-like property due to the **hh-κ type** dielectric mismatch effect.Such reality for the ***hh-k*** **type** Q2D structures is revealed for the first time. As obtained in Ref.6, the 2D Debye-Hückel type spatial dependence again to the moderately large in-plane distances range is established in the ***lh-k*** **type** Q2D structures with $\varepsilon_{r2} = \varepsilon_w/\varepsilon_{b2} \sim 1$.

The Q2D screening potential after Exp.(3) is weakened twice in comparison with Ref.6 result due to the interplay between two mutually exclusive cases of the dielectric mismatch effect (high-k and low-k) at one heterointerface of the QW structure. Besides that, $V_S(\rho)$ in both cases depends on the QW dielectric constant ε_w. That is quite natural because at the moderately large distances the dominant part of the screened Coulomb field passes through the confinement region and the dielectric heterogeneity of the QW structure only partially affects the Q2D screening potential behavior. Another important common feature of these cases is the explicit dependence on the QW thickness d for the 2D screening radius ρ_s .

Let us show the screened impurity ground state variational study both in the ***hh-k*** and ***lh-k*** **type** QW structures. In calculations, the 2D Debye-Hückel potential expressions are involved, respectively. Here for the screened impurity binding energy problem we have extracted the 2D screened exciton variational calculation results from the recent work [8] related to the ***lh-k*** **type** QW structures. Following that scheme, the screened impurity binding energy has been obtained by minimization of the variational functional by choosing the ground state normalized one- parameter trial wave function as

$$\psi(\rho) = \sqrt{2/\pi}\,\lambda\, e^{\lambda\rho}\,, \tag{4}$$

where λ is the variational parameter. The variational calculations for the lower bound on the screened impurity binding energy $E_b^{high\text{-}k}$ give:

$$E_b^{hh-k} = \frac{\hbar^2}{2m_e a_0^2}\left[2+\left(2-\frac{a_0}{\rho_s}\right)\sqrt{1+\frac{a_0}{\rho_s}}+\left(\frac{a_0}{2\rho_s}\right)^2\right]\left[\frac{\sqrt{1+(a_0/\rho_s)}-3}{\sqrt{1+(a_0/\rho_s)}+1}\right]. \tag{5}$$

Eq. (5) describes the screened impurity binding energy in the ***hh-k*** **type** QW structure and holds on if the nominator in the last term is negative.i.e. $\rho_s > (a_0/8)$.

Accordingly, for the ***lh-k*** **type** QW structure we will have:

$$E_b^{lh-k} = \frac{\hbar^2}{2m_e a_0^2}\left[8+\left(4-\frac{a_0}{\rho_s}\right)\sqrt{4+\frac{2a_0}{\rho_s}}+\left(\frac{a_0}{2\rho_s}\right)^2\right]\left[\frac{\sqrt{4+(2a_0/\rho_s)}-6}{\sqrt{4+(2a_0/\rho_s)}+2}\right]. \tag{6}$$

We receive an analytical expressions of the binding energy which gives us a good opportunity to illustrate more effectively an impurity screening problem in the discussed cases. In particular, as we may conclude from Exps. (5) and (6), for the moderately large in-plane distances ~ ρ_s an accounting of the low-κ dielectric mismatch in the one heteroboundary for the ***lh-k* type** QW structure highly rebalances the reduced binding associated with the high-κ dielectric mismatch effect for the two heterointerfaces in the ***hh-k* type** QW structure. This is clearly seen in the limit $q_s \rightarrow 0$ when the Q2D unscreened impurity binding energy instead of $4R_0$ takes the value as $16R_0$ [8], where $R_0 = \hbar^2 / 2m_e a_0^2$ - is the 3D impurity effective Rydberg.

As an illustration of the offered theoretical model let us now carry out the Q2D screened impurity property numerical calculations for the realistic InSb/HfO$_2$ interface. For that, the dielectric constants ratio is $\varepsilon_r = \varepsilon_w / \varepsilon_b = \varepsilon_{InSb} / \varepsilon_{HfO2} \approx 16.8 / 25 = 0.625$. The InSb bulk sample holds the smallest electron effective mass ($m^* \approx 0.014m_0$, m_0 - is the free electron mass)) and a macroscopically large impurity effective Bohr's radius as $a_0 \approx 63.7nm$. With this end, and in accordance with the strong condition $a_0 >> d$, we will display a numerical data for the QW width values $d < 10\ nm$ respectively. In Figs.1 and 2, the Q2D screened impurity binding energy dependencies as a function of parameter n_s/T for the fixed QW thickness d are presented for the ***HfO₂/InSb/HfO₂*** (***hh-k* type**) and ***vacuum/InSb/HfO₂*** (***lh-k* type**) QW structures respectively. As it follows from Figs.1 and 2, the binding energy parameters E_b^{hh-k} and E_b^{lh-k} start decreasing from the spatial confinement effect enhanced $E_b^{hh-k}|_{unsc} = =4R_0$ and spatial confinement +dielectric mismatch effects enhanced $E_b^{lh-k}|_{unsc} = =16R_0$ unscreened values with increasing the n_s/T parameter, where $R_0 = 0.66\ meV$ is the impurity Rydberg energy in the bulk InSb material. At that, the decrease of E_b^{hh-k} occurs mainly at the non-degenerate Q2D EG statistics. As we see from Fig.1 in the n_s/T parameter range $(1.2.10^7 \div 6.5.10^7)$ cm^{-2}/K^o we have the result E_b^{hh-k} >1meV, which indicates that a remaining binding is still sizable and points out the impurity bound state features in the discussed ***hh-k* type** structure. Whereas in the ***lh-k* type** structure for the range $(5.1.10^7\text{-}3.3.10^8) cm^{-2}/K^o$ due to the joined spatial confinement +dielectric mismatch effect influence, the energy parameter E_b^{lh-k} is quite enhanced and thus perceptible relatively to both ***hh-k* type** (E_b^{hh-k} >1 meV) and bulk sample structure R_0 = 0.66meV results. Meanwhile, for the ***lh-k* type** QW structure both Q2D EG statistics are significant and this fact is also reflected in Fig.2. Here we see the saturation of the E_b^{lh-k} parameter for the QW width values d < 8*nm*.

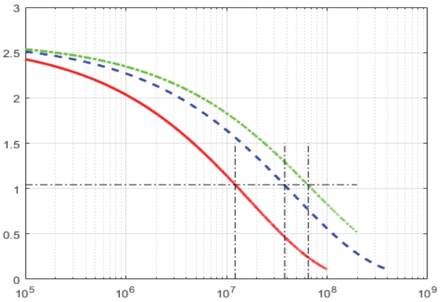

Fig. 1. The binding energy $E^{hh\text{-}k}$ of the screened impurity state as the function of n_s/T parameter for the QW width values of $d_1 = 2$nm (solid line), $d_2 = 6$ nm (dashed line) and $d_2 = 10$ nm (dashed-dotted line) for the ***HfO₂/InSb/HfO₂*** *as* ***hh-k type*** *structure*

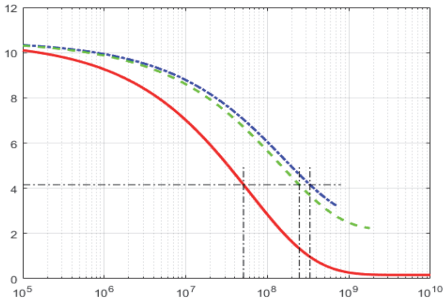

Fig. 2. The binding energy $E_b^{lh\text{-}k}$ of the screened impurity state as the n_s/T parameter for the QW width values of $d_1 = =2$nm (solid line) , $d_2 = 8$ nm (dashed line) and $d_2 = 10$ nm (dashed-dotted line) for the ***vacuum/InSb/HfO₂*** *as* ***hh-k type*** *structure*

As for the dependence of the impurity binding energy E_b on the QW width d, with an increase in d, we should expect an increase in E_b, which is demonstrated in the presented graphs. This behavior is entirely different from the results obtained in Ref. 5 for the ***ll-k* type** QW structure, where with an increase in d, E_b is decreasing.

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ԷԿՐԱՆԱՎՈՐՎԱԾ ԽԱՌՆՈՒԿԻ ԷՆԵՐԳԻԱՆ «ԲԱՐՁՐ-K» ՏԵՍԱԿՈՎ ԴԻԷԼԵԿՏՐԻԿԱԿԱՆ ՀԱԿԱԴՐՈՒԹՅԱՄԲ ՔՎԱՆՏԱՅԻՆ ՓՈՍՈՒՄ

Դիտարկված է քվանտային փոս / «բարձր-k» տեսակով արգելք դիէլեկտրիկական անհամապատասխանությանը վերաբերող խնդիր՝ ելնելով ելակետային սկզբունքներից: Դրա հաշվառումով առաջին անգամ քննարկված է էկրանավորված խառնուկի համար Դեբայ-Հյուկելի տիպի պոտենցիալի առանձնահատկությունների ազդեցությունը կապի էներգիայի վրա: Կատարված է ինչպես «*բարձր-k» -ով արգելք /քվանփային փոս / «բարձր-k» -ով արգելք*, այնպես էլ *«ցածր-k» -ով արգելք /քվանփային փոս / «բարձր-k» -ով արգելք* երկչափ համակարգերի դեպքերի թվային վերլուծություն InSb/HfO_2 հետերոանցման դեպքում:

Առանցքային բառեր. քվանտային փոս, խառնուկ, «բարձր-k» դիէլեկտրիկական հակադրություն:

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ЭНЕРГИЯ ЭКРАНИРОВАННОЙ ПРИМЕСИ В КВАНТОВОЙ ЯМЕ С ДИЭЛЕКТРИЧЕСКИМ КОНТРАСТОМ ТИПА “ВЫСОКИЙ-k”

Рассмотрена проблема диэлектрического рассогласования типа квантовая яма / диэлектрический барьер с “высоким-к”, исходя из исходных принципов. С учетом этого впервые обсуждено влияние аналитических особенностей экранированного потенциала взаимодействия типа Дебай-Хюккеля на энергию связи. Проведен комплексный численный анализ двумерных структур как для случая *барьер с “высоким-к”/квантовая яма / барьер с “высоким-к”*, так и для случая *барьер с “низким-к”/квантовая яма/барьер с “высоким-к”* на основе гетероперехода InSb / HfO2.

Ключевые слова: квантовая яма, примесь, диэлектрический контраст типа “высокий-к”.