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Laser and electric field dependence on donor impurity in a quantum wire

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Calculation of the binding energy of an axial donor hydrogenic impurity, dressing by light in the cylindrical quantum wires made up of different materials placed in presence of electric field is reported. A rapid decrease of the binding energy for different values of the wire radius with increasing high frequency laser field intensity in the presence of electric field is predicted. Si wire is found to have the maximum efficiency and less binding energy when compared to other materials like GaAs and CdTe. This technology may be implemented in place of conventional solar panel, Si quantum wires can be embedded on a nonconducting material. The binding energies are found to increase with decrease in the wire radius upto the Bohr radius of the material , and decrease with increase in the value of the laser field amplitude λ in all cases. A rapid decrease in binding energy is observed when the electric field is applied. This is an elegant model that can be used in place of conventional solar panel so as to increase the efficiency of the solar panel.

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1. Introduction

In recent years, quasi-one dimensional semiconductor quantum well wires (QWWs) have been fabricated in a variety of geometric shapes with atomic scale definition and electronic transport through the QWWs wire has been studied intensively theoretically as well as numerically [1,2]. Optical properties of electrons confined to nano-dimensions are of interest for optical and electronic devices. As the dimensionality of the structure is reduced, the density of states tends to bunch together leading to a singularity in the 1D case. This effect can be very useful for low-threshold laser applications. Quantum confinement leads to an increase in the binding energy and provides possibilities for much better performance of optical devices such as semiconductor lasers. QWW optical properties have been studied for their potential device applications such as semiconductor lasers [3,4]. Quantum wire lasers should show outstanding performance because of enhanced density of states at the bottom of conduction and valence bands [5].

$Ga_{1-x}Al_xAs$ is one of the most important ternary III-V compound semiconductors. It is found that the QWR laser structures are a promising choice because of the many predicted benefits, such as higher gain, reduced temperature sensitivity, higher modulation bandwidths, and narrower spectral line widths [6]. During the recent years, there has been increasing interest and considerable experimental and theoretical activity focused on the semimagnetic semiconductors, also called diluted magnetic semiconductors (DMS) [7,8]. These compounds have some unique properties leading to their potential use in a wide range of opto-electronic applications. Since 1977, when Kamarov et al., [9] first reported the giant enhancement of magnetic-optical effects in $Cd_{1-x}Mn_xTe$, much effort has been directed towards the understanding of the physics underlying the unusual phenomena associated with these special semiconductors. Semiconducting nanowires are very promising building block for future nanoelectronic and nanophotonic applications as witnessed by several recently demonstrated devices [10,11]. Silicon, one of the most relevant materials from the technological point of view, has excellent electronic and optical properties as a semiconductor. Silicon nano-wires are especially attractive candidates due to their compatibility with conventional Si-technology and due to the accurate control of diameter and electronic properties during synthesis [8]. Recently, a Si nano-wire with a length comparable to the de Broglie wavelength of carriers is realized by advanced nanofabrication technique [12,13]. The cross-sectional area of Si nano-wires was designed to show well-separated transverse modes and electrons confined to the wire are expected to suffer from a minimal amount of impurity scattering.

These properties make the Si nano-wires good candidates for the study of ballistic quantum transport. In addition, the potential distribution within the wire can be controllable by a metallic gate around the wire. This provides additional degree-of freedom on currents through the device and one would expect that the basic transistor action is possible for a Si nano-wire. As a result, the gate-all-around Si wire may shed the light on one-dimensional structures for future transistor applications [14].

During the last two decades low-dimensional semiconductor structures find wide applications in optoelectronic devices. Up to now, many efforts have been devoted to the realization of QWW lasers. More recently the effect of intense electric field created by high intensity laser field on optical and electronic properties have been extended to Low Dimensional Semiconducting systems (LDSS) like Quantum Well [15], Quantum Well Wire [16] and Quantum Dot [17,18]. A prominent example is their use as active regions in lasers. Quantum structure lasers are expected to show improved device properties such as low threshold current, high optical gain [19], and low temperature sensitivity [20]. Optical transitions in quantum well wires under intense laser field was studied recently by Sari et al., [21].

In the present work, the binding energies of the donor impurities, in Si/Ge, GaAs/GaAlAs, and $Cd_{1-x_{in}}Mn_{x_{in}}Te/Cd_{1-x_{out}}Mn_{x_{out}}Te$ quantum wires, are performed using the effective mass approximation within a variational scheme. Calculation of the binding energy of an axial donor hydrogenic impurity in a cylindrical quantum wire placed in an intense, high-frequency laser field is reported. A systematic study of variation of electric field as the function of wire size has been attempted to calculate the binding energies of impurities in the influence of the intensity and frequency of the laser field. We propose an elegant model that can be used in place of conventional solar panel so as to increase the efficiency of the solar panel. Quantum wires of these different materials embedded on a nonconductive plastic medium maximize the efficiency of its performance when a small amount of electric field is applied. The results are then compared with the existing data available. The method followed is presented in the Section 2 while the results and discussion are provided in the Section 3.

2. Theory and model

The time dependent Schrödinger equation describing the interaction dynamics is transformed by Kramers [22]

$$-\frac{\hbar^2}{2m^*}\nabla\Psi(\vec{r},t)+V(\vec{r}+\vec{\alpha}(t)\Psi(\vec{r},t)=-i\hbar\frac{\partial\Psi(\vec{r},t)}{\partial t} \quad (1)$$

here

$$\vec{\alpha}(t)=e\alpha_0\sin(\omega t), \quad \alpha_0=\frac{eA_0}{m^*\omega} \quad (2)$$

Describes the motion of the electron in the laser field and α_0 is the laser dressing parameter, e and m* are the charge and effective mass of the electron respectively.

In the high frequency limit [23] the laser dressed eigenstates are the solutions of the time independent Schrödinger equation

$$-\frac{\hbar^2}{2m^*}\nabla+V_d(\vec{r},\vec{\alpha}_0)\phi=E\phi \quad (3)$$

where $V_d(\vec{r},\vec{\alpha}_0)$ is the laser dressed potential given by

$$V_d(\vec{r},\vec{\alpha}_0)=\frac{\omega}{2\pi}\int_0^{2\pi/\omega}V(\vec{r}+\vec{\alpha}(t))dt. \quad (4)$$

In the Coulomb potential case $V(\vec{r})=-\frac{e^2}{4\pi\varepsilon_0|\vec{r}-\vec{r}_i|}$ where $\vec{r}_i$ is the position of the impurity, the, the dressed potential has the form [24]

$$V_C(\vec{r},\vec{\alpha}_0)=-\frac{e^2}{4\pi\varepsilon_0}\left[\frac{1}{|\vec{r}-\vec{r}_i+\vec{\alpha}_0|}+\frac{1}{|\vec{r}-\vec{r}_i-\vec{\alpha}_0|}\right]. \quad (5)$$

We consider the z-axis to be along the growth direction of the well. The Hamiltonian of the system consisting of an electron bound to a donor ion inside the quantum well wire in the presence of an intense high frequency laser field and an external longitudinal electric field is given by

$$H=\frac{p_\perp{}^2}{2m^*}+H_z+V_C(\vec{r},\vec{\alpha}_0) \quad (6)$$

where $\frac{p_\perp{}^2}{2m^*}$ is the kinetic energy operator in the xy plane and H_z is the Hamiltonian in the z-direction, the case of impurity absence. If we assume the laser field polarization parallel to the z-direction, the subband Hamiltonian can be written as

$$H=-\frac{\hbar^2}{2}\frac{d}{dz}\left(\frac{1}{m^*(z)}\frac{d}{dz}\right)+V(z,\alpha_0)+eFz \quad (7)$$

where F is the externally applied electric field, and $V(z,\alpha_0)$ is the dressed confinement potential of the well taken to be 25 R_y^* throughout the calculation.

Since an exact solution of the Schrödinger equation with the Hamiltonian in Eq. (6) is not possible, a variational approach has been adopted. The wave function of the laser dressed hydrogenic donor is given by

$$\psi_{in} = A\cos(k_1 z)(1+\beta Fz)\exp(-\alpha\sqrt{(\rho^2+z^2+a^2})$$
$$r < R$$

$$\psi_{out} = B\exp(-k_{21} z)(1+\beta Fz)\exp(-\alpha\sqrt{(\rho^2+z^2+a^2})$$
$$r \geq R \quad (8)$$

where $k_1 = \sqrt{2m^* E_s/\hbar^2}$, $k_2 = \sqrt{2m^*(V(z)-E_s)/\hbar^2}$, E_s is the subband energy and V is the equivalent barrier height. Here A and B are normalization constants and α and β are the variational parameters. The

subband energy is calculated by solving the transcendental equation $\sqrt{E_s/V(z)} = \cos(L\sqrt{2m^* E_s/\hbar^2})$ numerically. This fixes the values of k_1 and k_2 for the lowest values of E_s. By matching the wave functions and their derivatives at boundaries of the wire and along with the normalization, we fix all the constants except the variational parameter.

The Schrödinger equation is solved variationally by finding $\langle H \rangle_{\min}$ and the binding energy of the donor in a quantum wire is given by the difference between the energy with and without Coulomb term.

3. Results and discussion

We have calculated the values of the binding energy of a laser dressed donor where the impurity is located along the axis of the quantum-wire in the presence of electric field. The units of length and energy used throughout are the effective Bohr radius $R^* = \hbar^2\varepsilon_o/m^*e^2$ and the effective Rydberg $R_y^* = m^*e^4/2\varepsilon_o^2\hbar^2$ where ε_o is the dielectric constant and m* is the effective mass of electron in the conduction band minimum.

Table 1 shows the variation of subband energy for different electric fields with the wire radius of GaAs. It is clear from the table that the subband energy increases as the wire radius decreases. The subband energy decreases when the electric field is applied for any wire radius. The negative energies arise due to the asymmetry introduced by the electric field in the wire [25]. As the electric field becomes larger, the asymmetry introduced is more, resulting high negative subband energy. Fig. 1 shows the radial spreading in the electronic probability density for various intense laser fields with the radius of the wire. It follows that the wave function is compressed as the external perturbation is applied.

Table .1 Variation of Subband Energy (R_y^*) for different electric fields with the wire radius

Wire Radius (Å)	Subband Energy (R*)			
	5×10^3 V/m	10^4 V/m	5×10^4 V/m	10^5 V/m
1000	0.298	-0.032	-0.461	-5.122
700	0.429	-0.167	-0.292	-3.485
500	0.607	0.025	-0.170	-2.368
200	1.592	0.235	0.168	-0.551
100	3.362	0.768	0.741	0.463
90	3.768	0.908	0.885	0.650
80	4.280	1.093	1.074	0.880
70	4.941	1.343	1.228	1.176
60	6.548	1.845	1.789	1.658
50	7.055	2.230	1.68	1.584
40	8.859	3.100	3.058	2.984
30	11.688	4.712	4.654	4.521
20	16.472	8.341	8.251	8.129
10	24.668	18.213	18.204	17.458

[a]The negative energies arise due to the asymmetry introduced by the electric field in the wire [25].

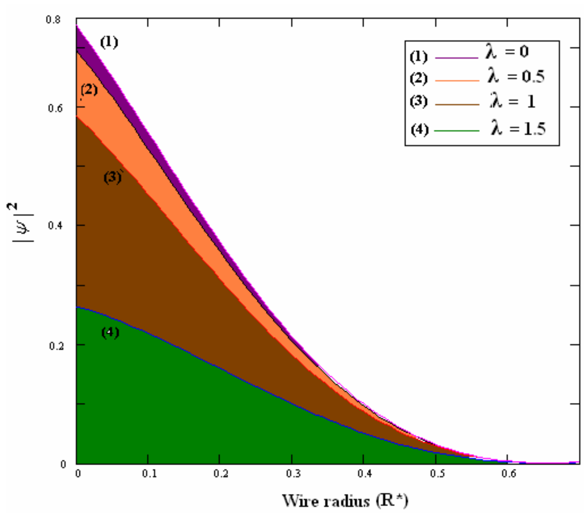

Fig. 1. Electron probability density with the wire radius in the presence of electric field and the measure of intensity of laser field.

Fig. 2 illustrates an elegant model that can be used in place of conventional solar panel so as to increase the efficiency of the solar energy. Using quantum wires of GaAs embedded on a nonconductive plastic maximizes the conductivity. After receiving the sufficient light, the eliberated electrons are attracted by the opposite polarity of the electrode increasing the conductivity. The quantum wires are also sandwiched between conductive plastic media if light falls on the quantum wire then the chance that an electron can escape from the quantum wires and reach conductive plastic, that also been stripped of an electron, thereby increasing the conductivity.

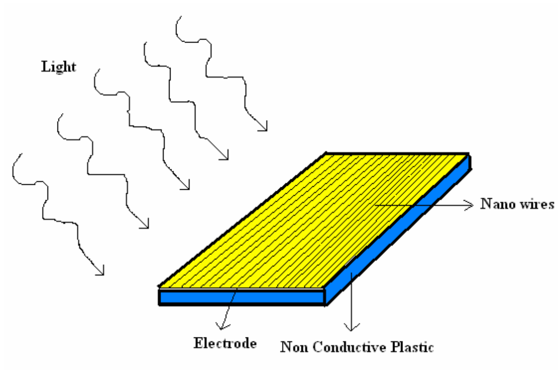

Fig. 2. Solar cell using nanotechnology by quantum wires on the nonconductive plastic medium.

In Fig. 3, we present the variation of laser dressed donor ionization energy with the dot radius of GaAs wire with and without applying electric field. As the wire radius decreases the donor ionization energy increases up to one effective Bohr radius (103Å) and then decreases when the radius of wire is so small due to tunneling of electrons through the barrier λ = 0. We observe that the donor ionization energy decreases drastically as intensity of the laser field increases [26,27,28]. For large values of laser field parameter the wave function of the particle start to spill over into the barrier material, i.e., the electron becomes less confined, which leads to a smaller Coulomb interaction and therefore a lower binding energy [27].

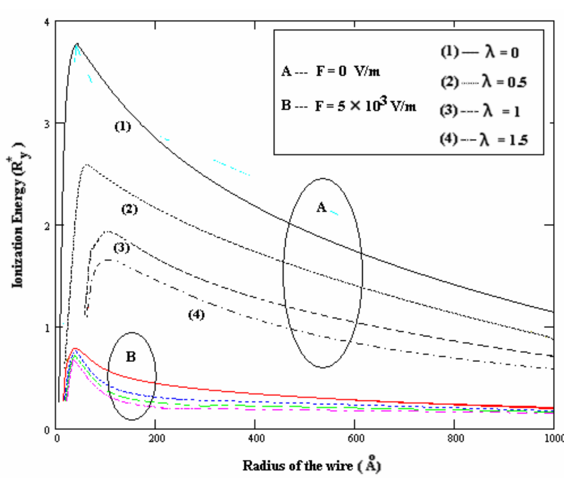

Fig. 3. Variation of ionization energy with the dot radius for different field of intensities with and without the electric field in a GaAs wire.

When the intensity increases the unbound state occurs before the radius of the wire approaches the effective Bohr radius. This feature is predominant for lower radius of the quantum wire. When no laser field is applied (λ = 0) our result agrees with the result of Ref.[25]. The efficiency of ionization energy increases by 40% when the measure of laser intensity is increased by 0.5 in the absence of electric field. This efficiency is doubled when the strength of electric field becomes 5 kV/m.

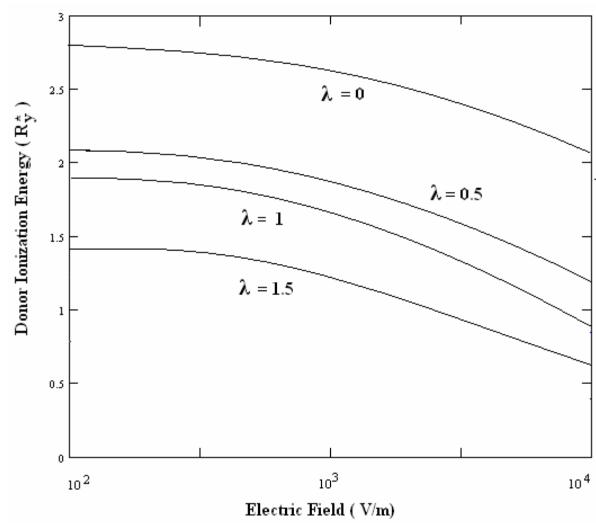

Fig. 4. Variation of donor ionization energy with the electric field for different intensity of laser field for the wire radius of 20Å.

Fig. 4 shows the variation of donor ionization energy with the electric field for different intensity of laser field for the wire radius of 20 Å. It shows that binding energy decreases with the electric field for all the wire radii whether it is irradiated or not as expected. However, the binding energy still decreases with the increase of laser field and this character is leading for all smaller wire radii. The efficiency of ionization energy increases by 55% when the measure of laser intensity is increased by 0.5 with the small electric field strength of 10^2 V/m. The additional 22% efficiency is achieved just by applying electric field strength of 10^2 V/m. As far as we are concerned, a few more reports have been made earlier. L.Fraas et al., [29] have found the infrared-sensitive GaSb cells and visible-light-sensitive GaAs cells designed for satellite applications with the efficiency of 28.1% under concentrated sunlight. Khaselev et at., [30] have reported to be over 16% by for GaAs/GaInP_2 system in calculating the solar-to-hydrogen conversion efficiency and the measurements were obtained both indoors under 100-mW/cm^2 insolation, and outdoors. This feature has clearly brought out in the Fig.5. We have plotted the variation of donor ionization energy with intensity of laser field for different strength of electric fields for the wire radius of 20 Å. The binding energy decreases with the intensity of laser field increases for all the wire radii in the presence of electric field. This feature is predominant for lower radius of the quantum-wire as well as the applied electric field.

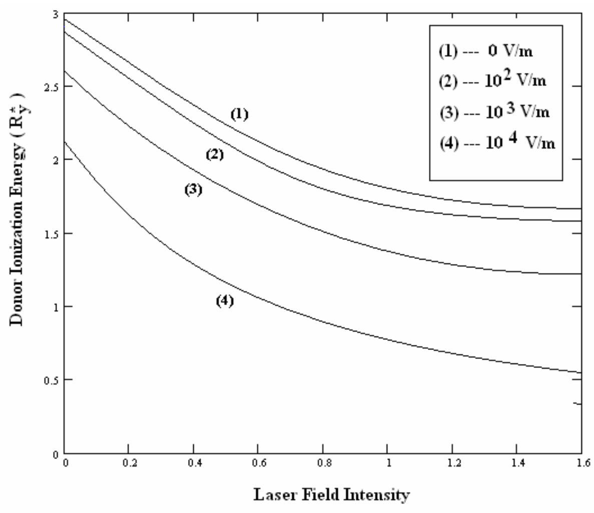

Fig. 5. Variation of donor ionization energy with intensity of laser field (measureless quantity) for different strength of electric fields for the wire radius of 2Å.

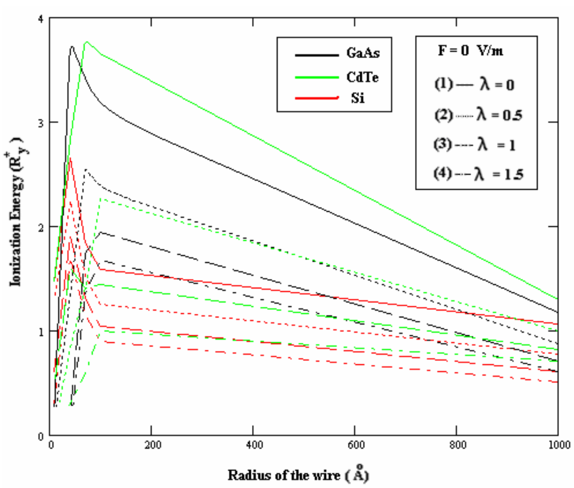

Fig. 6. Shows the variation of th ionization energy with the dot radius in the influence of light intensity for all the wire radii of CdTe, Si , GaAs in the absence of electric field.

Fig. 6 shows the variation of ionization energy in the influence of light intensity for all the wire radii of CdTe, GaAs and Si in the absence of electric field. All the materials depict the same behaviour whereas Si wire shows the less binding energy for all the wire radii of different materials. Also binding energy decreases while shining the intense laser radiation for all the materials. The efficiency doubles when Si wire is used in the presence of laser field when compared with the other materials such as CdTe and GaAs wires. So the suitable material for making arrays of quantum-wires on the solar panel is Si wire which will be replaced in place of conventional films.

In conclusion, the variational approaches are used in a thorough study of the ionization energy of on-center shallow donors in a quantum-wire of $Cd_{1-x_{in}}Mn_{x_{in}}Te/Cd_{1-x_{out}}Mn_{x_{out}}Te$, GaAs/GaAlAs and Si/Ge. The dressed laser donor ionization energies are calculated in the presence of electric field. And its efficiency is found to be doubled when Si wire is used in the presence of both the laser and electric fields. This elegant model can be replaced with the conventional solar panel and found to increase the efficiency of solar energy when quantum-wires are embedded on the conductive plastic medium in the solar panel. However, we have used the high intense laser light to calculate the efficiency of ionization energy; experimental efforts are encouraged to lend support to our calculations.

References

[1] P. Hänggi, M. Ratner, and S. Yaliraki, Chem. Phys. **281**, 111 (2002).
[2] A. Nitzan, M. A. Ratner, Science **300**, 1384 (2003).
[3] V. V. Mitin, V. A. Kochelap, M. A. Stroscio,Quantum Hetrostructures: Microelectronics and Optoelectronics, Cambridge University Press, 1999
[4] P. Harrison, Quantum Wells, Wires and Dots, John Wiley and Sons,2000.
[5] Y. Arakawa, H. Sakaki, Appl. Phys. Lett. **40**, 939 (1982).
[6] D. E. Wohlert, S. T. Chou, A. C Chen, K. Y. Cheng, K. C. Hsieh, Appl. Phys. Lett. **17**, 2386 (1996).
[7] Diluted Magnetic Semiconductors, Mukesh Jain, World Scientific (1991).
[8] J. K. Furdyna, J. Kossut, in Diluted Magnetic Semiconductors, edited by J. K. Furdyna, J. Kossut, Semiconductors and Semimetals, Vol. 24, edited by R. K. Willardson and A. C. Beer (Academic Press, N. Y., 1988).
[9] A. V. Kamarov, S. M.Pjabchenko, O. V. Terletskii, I. I. Zheru, R. D. Ivanchuck, Zh. Eksp. Teor. Fiz, **73**, 608 (1977).
[10] L. Samuelson, C. Thelander, M. T. Björk, M. BÖrgstrom, K. Deppert, K. Dick, A. Hansen, T. M årtensson, N. Panev, A. Persson, et al., Physica E **25**, 313 (2004).
[11] Y. Wu, C. Yang, W. Lu, C. M. Lieber, Nature, **430**, 61 (2004).
[12] Y. Wu, Y. Cui, L. Huynh, C. Barrelet, D. Bell, and C. Lieber, Nano Lett. **4**, 433 (2004).
[13] K. H. Cho, Y. C. Jung, B. H. Hong, S. W. Hwang, J. H. Oh, D. Ahn, S. D. Suk, K. H. Yeo, D. Kim, D. Park, W. S. Lee, Appl. Phys. Lett. **90**, 182102 (2007).
[14] Jung Hyun Oh, D. Ahn Y. S. Yu S. W. Hwang,Phys. Rev. B **77**, 035313 (2008)
[15] Ecaterina Niculescu, Anca Iorga, Adrian Radu, U.P.B. Sci. Bull., Series A, **70**, 2(2008).
[16] D. Piester, P. Bönsch, T. Schrimpf, H.-H. Wehmann,

A. Schlachetzki, IEEE J. Quantum Electron, **6**, 522 (2000).
[17] Qu Fanyao, A. L. A. Fonseca, O. A. C. Nunes, Phys. Rev. B **54**, 16405 (1996).
[18] L. E. Oliveira, L. E. Large, H. S. Brandi, Phys.Stat.Sol(b). **190**, 667(2002)
[19] M. Asada, Y. Miyamoto, Y. Suematsu, IEEE J. Quantum Electron. **22**, 1915(1986).
[20] Y. Arakawa, H. Sakaki, Appl. Phys. Lett. **40**, 939 (1982).
[21] H. Sari, E. Kasapoglu, L.Sökmen, M. Güne, Phys.Lett.A.**319**, 211 (2003).
[22] H. Kramers, Collected Scientific Papers, North-Holland, Amsterdam, 866 (1956).
[23] M. Marinescu, M. Gavrila, Phys. Rev. A **53**, 2513 (1995).
[24] F. Ehlotzky, Phys. Lett. A **126**, 524 (1988).
[25] A. John Peter, K. Navaneethakrishnan Physica B **366**, 146(2005).
[26] Y. P. Varshini, Superlatt. and Microstruct. **30**, 46 (2001).
[27] E. C. Niculescu, A. M. Radu, J. Optoelectron. Adv. Mater. **9**, 3598 (2007).
[28] E.C.Niculescu, L.Burileanu, J. Optoelectron. Adv. Mater. **9**, 2713 (2007).
[29] L. Fraas, J. Avery, J. Martin, V. Sundaram, G. Girard, V. Dinh, N. Mansoori, J. W. Yerkes, Energy Conversion Engineering Conference, 1989. IECEC-89., Proceedings of the 24th Intersociety **6-11**, 815-820 (1989).
[30] O. Khaselev, A. Bansal, J. A. Turner, Int. J. Hyd. En. **26**, 127(2001).

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