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ENHANCEMENT OF THE ELECTRONIC CONFINEMENT IMPROVES THE MOBILITY IN P-N-P DELTA-DOPED QUANTUM WELLS IN SI

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Abstract—The electronic structure and mobility trends in a n-type delta-doped quantum well in Si, matched between p-type delta-doped barriers of the same material, is presented. The distance between the n-type well and p-type barriers is varied from 50 Å to 500 Å; and also the impurity density from $5 \times 10^{12}\,\mathrm{cm}^{-2}$ to $5 \times 10^{13}\,\mathrm{cm}^{-2}$, for both, donors and acceptors. An increase in the mobility by a factor of 1.6 at interwell distance of 50 Å with donor and acceptor concentrations of $5 \times 10^{12}\,\mathrm{cm}^{-2}$ and $5 \times 10^{13}\,\mathrm{cm}^{-2}$ compared with a single delta-doped well without p-type barriers is found. This improvement in mobility could be attributed to a better confinement of carriers, which favors excited levels with nodes in the donor plane. This trade-off between carrier concentration and mobility could be exploited in high-speed, high-power and high-frequency applications.

1. INTRODUCTION

Carrier densities two-three orders of magnitude greater than those reported in $GaAs$ systems can be achieved in Silicon systems by means of delta-doping [1]. So, the delta-doped quantum wells in Si are

ideal structures to study the transport properties of ultradense two dimensional electron gases (2DEG) [2, 3] These works make emphasis in parameters such as the mobility, mean free path, and phase coherent length due to their implications in ballistic and coherent nanodevices. Meanwhile the carrier concentration in this kind of systems is ultra high, the mobility is very low, which is opposite to the behavior in $GaAs/AlGaAs$ systems [4]. An improvement in the conductivity not properly the mobility could be reach via the coupling of delta-doped layers [5]. The main proposal relies in finding the interwell distance at which the mobility is maximum in conjunction with the high carrier density coming from the two delta-doped planes, such that the conductivity -the product of the mobility and the carrier density-enhances [6].

In the present paper we propose and study the implications of matching a n-type delta-doped quantum well in Si between p-type delta-doped barriers ($pnpDD$) of the same material. We analyzed the electronic structure and specially the mobility trends as a function of the interlayer distance and the impurity concentration. The Thomas-Fermi approximation and the effective mass theory are used in order to obtain the confining potential and the electron subband levels, respectively. Meanwhile the mobility calculations are performed via an empirical formula previously proposed and applied to n, p, and p-n delta-doped systems [5, 7, 8]. We find that the electron confinement plays an important role to optimize the mobility. We observed an increase of nearly 60% in the mobility at interwell distance of 50 Å and donor and acceptor concentrations of 5 and 50 in units of $10^{12}\,\mathrm{cm}^{-2}$.

2. MATHEMATICAL METHOD

For a single n-type δ-doped quantum well in Si centered at $z = a$ the confining potential can be written as [5],

$$V^*_{Hn}(z) - \mu^*_n = -\frac{\beta^2}{(\beta\,|z-a| + z_{0n})^4}, \tag{1}$$

with $\beta = \frac{2}{15\pi}$ and $z_{0n} = \left(\frac{\beta^3}{\pi n^{au}_{2D}}\right)^{1/5}$. $V^*_{Hn} = V_{Hn}/R^*_{yn}$ and $\mu^* = \mu/R^*_{yn}$ are given in units of the effective Bohr radius and effective Rydberg, $a^*_{0n} = \frac{\epsilon_r \hbar}{m^* e^2}$ and $R^*_{yn} = \frac{e^2}{2\epsilon_r a^*_{0n}}$.

In the case of a single p-type δ-doped quantum well in Si centered at $z = b$ the confining potential can be written as [9],

$$V^*_{Hp}(z) - \mu^*_p = \frac{\alpha^2}{(\alpha\,|z-b| + z_{0p})^4}, \tag{2}$$

with $\alpha = \frac{2m_a^{3/2}}{15\pi}$ and $z_{0p} = \left(\frac{\alpha^3}{\pi p_{2D}^{au}}\right)^{1/5}$. $V_{Hp}^* = V_{Hp}/R_{yp}^*$ and $\mu_p^* = \mu/R_{yp}^*$ are given in units of the effective Bohr radius and effective Rydberg, $a_{0p}^* = \frac{\epsilon_r \hbar}{m_{hh}^* e^2}$ and $R_{yp}^* = \frac{e^2}{2\epsilon_r a_{0p}^*}$.

The next step is the construction of the $pnpDD$ potential, so, if we consider the same impurity density in both p-type planes the system is symmetric with respect to the middle of the n-type one, then we can restrict ourselves to the half of the plane ($z \leq 0$) and the potential can be written as

$$V_H^*(z) = -\frac{\beta^2}{(\beta\,|z| + z_{0n})^4} + \frac{\alpha^2}{(\alpha\,|z+l| + z_{0p})^4} \tag{3}$$

where a and b have been taken as 0 and l.
The latter equation summarizes the model for the conduction band bending profile. Instead of carrying out numerically troublesome self-consistent calculations, we simply solve Schrödinger-like effective mass equations at the zone center $\mathbf{k} = \mathbf{0}$, thus obtaining the corresponding subband longitudinal and transverse electron levels.

For the mobility calculations we implement an empirical formula previously proposed and applied to n, p and p-n delta-doped systems [5, 7, 8],

$$\mu_{rel}^{\delta} = \frac{\mu_{pnpDD}}{\mu_{SDD}} = \frac{\iint \rho_e^{\delta}(z')\rho_{imp}^{\delta}(z)\,|z-z'|\,dzdz'}{\iint \rho_e^{pnp\delta}(z')\rho_{imp}^{pnp\delta}(z)\,|z-z'|\,dzdz'}, \tag{4}$$

where ρ_e^{δ} and ρ_{imp}^{δ} ($\rho_e^{pnp\delta}$ and $\rho_{imp}^{pnp\delta}$) represent the density of electrons and impurities of SDD (of $pnpDD$), respectively. Substituting the density of electrons and impurities and integrating over z we obtain,

$$\mu_{rel}^{\delta} = \frac{\sum_{ij} m_j \int \left|F_{ij}^{\delta}(z')\right|^2 (k_F^{\delta} - E_{ij}^{\delta})\,|z'|\,dz'}{\sum_{ij} m_j \int \left|F_{ij}^{pnp\delta}(z')\right|^2 (k_F^{pnp\delta} - E_{ij}^{pnp\delta})\,|z'|\,dz'}, \tag{5}$$

where $F_{ij}^{\delta}(z')$, k_F^{δ} and E_{ij}^{δ} ($F_{ij}^{pnp\delta}(z')$, $k_F^{pnp\delta}$ and $E_{ij}^{pnp\delta}$) are the envelope function, the Fermi level and the ith level respectively of the SDD (of $pnpDD$).

3. RESULTS AND DISCUSSION

We have used standard parameters for n- and p-type Silicon [5, 10]. The donor and acceptor concentrations varies from $1 \times 10^{12}\,\mathrm{cm}^{-2}$ to $1 \times 10^{14}\,\mathrm{cm}^{-2}$.

In Fig. 1, we depict the potential profile of p-n-p delta doped quantum wells in Si for various distances with (a) $n_{2D} = 5 \times 10^{12}\,\mathrm{cm}^{-2}$ and $p_{2D} = 5 \times 10^{12}\,\mathrm{cm}^{-2}$ and (b) $n_{2D} = 5 \times 10^{12}\,\mathrm{cm}^{-2}$ and $p_{2D} = 5 \times 10^{13}\,\mathrm{cm}^{-2}$. It is worth mentioning that in all calculations performed only the ground states for longitudinal and transverse electrons are occupied due to the multiple valley degeneracy present in n-type Silicon.

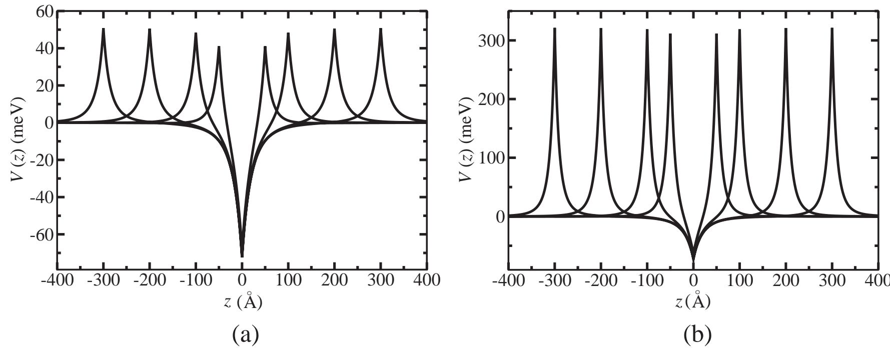

Figure 1. Potential profile of $pnpDD$ QW's for different interwell distances. (a) and (b) corresponds to acceptor concentrations of 5 and 50 in units of $10^{12}\,\mathrm{cm}^{-2}$. The donor density is fixed at 5 in units of $10^{12}\,\mathrm{cm}^{-2}$.

In Fig. 2, we present the mobility of p-n-p delta doped quantum wells in Si versus the distance between the donor and acceptor planes. We have fixed the donor concentration at $5 \times 10^{12}\,\mathrm{cm}^{-2}$, and taken three values for the acceptor one, $5 \times 10^{12}\,\mathrm{cm}^{-2}$, $10 \times 10^{12}\,\mathrm{cm}^{-2}$ and $50 \times 10^{12}\,\mathrm{cm}^{-2}$, solid, dot and dash lines, respectively. There are two important trends in the mobility: (1) the monotonic decrease as the p-type barriers are separated from the n-type well and (2) an increase as the acceptor concentration is raised. We find an increase in the mobility of 23%, 32% and 60% at a interplane distance of 50 Å for the three acceptor densities mentioned above. These results reflects that a more effective confinement of electrons could be used as a mechanism to improve the transport properties in delta-doped systems.

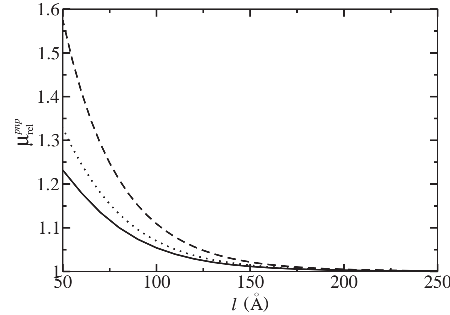

Figure 2. Relative mobility versus the distance between the n-type well and the p-type barriers. The donor density remains fix at $5 \times 10^{12}\,\mathrm{cm}^{-2}$, meanwhile the acceptor concentration takes three values 5 (solid), 10 (dot) and 50 (dash) in units of $10^{12}\,\mathrm{cm}^{-2}$.

4. CONCLUSION

In summary, we study the electronic subband structure and mobility trends of a n-type delta-doped quantum well in Si matched between p-type barriers of the same material. We have analyzed the effects of two paramount parameters in the system, the distance between the n-type well and the p-type barriers, and the impurity density in the donor and acceptor planes. We find a more effective confinement as the p-type barriers are closer to the n-type well, and we also observe the same effects as the acceptor concentration is raised, which is reflected in an improvement of the mobility of nearly 60%. So, the interplane distance and the impurity density could be used as natural tunning parameters to improve the transport properties in delta-doped systems via enhancement of the electron confinement.

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