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Citation: Chin. Phys. B . 2019, 28(4): 046102. **doi:** 10.1088/1674-1056/28/4/046102
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Delta-doped quantum wire tunnel junction for highly concentrated solar cells

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(Received 2 December 2018; revised manuscript received 15 February 2019; published online 19 March 2019)

We propose a novel structure for tunnel junction based on delta-doped AlGaAs/GaAs quantum wires. Higher spatial confinement of quantum wires alongside the increased effective doping concentration in the delta-doped regions extremely increase the peak tunneling current and enhance the performance of tunnel junction. The proposed structure can be used as tunnel junction in the multijunction solar cells under the highest possible thermodynamically limited solar concentration. The combination of the quantum wire with the delta-doped structure can be of benefit to the solar cells' advantages including higher number of sub-bands and high degeneracy. Simulation results show a voltage drop of 40 mV due to the proposed tunnel junction used in a multijunction solar cell which presents an extremely low resistance to the achieved peak tunneling current.

Keywords: delta-doping, quantum wire, solar cell, tunnel junction

PACS: 61.72.–y, 68.65.La, 88.40.H–, 73.43.Jn **DOI:** 10.1088/1674-1056/28/4/046102

1. Introduction

Tunnel junctions (TJs) play a significant role in different optoelectronic devices. In multijunction solar cells, the tunnel junction allows photo-generated carriers to pass through the solar cell with minimum loss.[1] The multijunction solar cells used in higher solar-radiation concentrations have an essential requirement for tunnel junctions with high peak-to-valley current ratio,[2] which may be achieved by increasing the doping concentration of p- and n-type layers. However, it is hard to experimentally increase the doping concentration to a very high level.[3] For multijunction solar cells, the tunnel junction can provide a contact that exhibits high peak current, low resistive loss (*i.e.*, voltage drop) and low optical loss. Both peak current and optical loss are related to the band gap in the junction region. As is well known, the tunneling process can be accelerated by creating an engineered energy level in order to gather the electrons. Utilizing the quantum confined structures is one of the methods for bandgap engineering aims. The investigation of energy-band diagrams emphasizes that the existence of internal sub-bands can greatly enhance the tunneling probability of carriers.[4] The internal sub-band region can be achieved by implementing the quantum well/wire structures through inserting a nano-scale low band-gap material between highly doped p- and n-type layers of the conventional tunnel junction.[5,6] It is obvious that the middle low band-gap layer makes a suitable region for the electrons established in the n-type region to be transmitted to the p-type region. So, the high carrier confinement in quantum-confined structure results in an improved tunnel device to be used in multijunction solar cells. However, in spite of recent improvement in quantum-structured tunnel junctions,[6,7] it seems that they cannot support the requirements for the future concentrated solar cells. Because the theoretical predictions based on thermodynamic limits and experimental achievements about highest possible solar concentration emphasize that the new multijunction solar cells require the improved tunnel junctions with the capability of passing the current density up to 4.6×10^4 times that of conventional unconcentrated solar cells.[8–10]

The high current density can be achieved with the extensive increase of doping concentration level. Most of the recent simulation-based researches focus on the highly-doped region in order to achieve a suitable peak tunneling current. However as previously explained, it is hard to implement very high p^{++} and n^{++} doping concentration. Therefore, we are trying to solve this problem by introducing a novel structure based on the reasonable doping concentrations. Delta-doping technique is a promising method which can be utilized to increase the effective doping concentration and consequently enhance the peak tunneling current of tunnel junction in comparison with those of the simple counterparts.[11,12]

In this paper, a novel structure for tunnel junction is presented based on delta-doped quantum wires (DDQWRs) in order to extremely increase the tunneling probability. The proposed structure consists of five 6nm GaAs intrinsic quantum wires which are narrowly doped with p- and n-type materials in two 7.5 Å regions. Although the very high current density is not applicable according to limitations about the highest pos-

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sible solar concentrations, the presented delta-doped quantum wire structure allows us to design the tunnel junctions with the capability of passing the tunneling current even higher than 1480 A/cm^2 in the case. It should be mentioned that all of the experimental requirements have been considered in our simulations. The finite element method (FEM) is utilized to simulate the proposed tunnel junction. The simulation of transport of carriers through the structure can be accomplished by applying a set of differential equations, derived from Maxwell's equation, to grids.

The rest of this paper is organized as follows. In Section 2 we present the design procedure of the proposed quantum wire and delta-doped quantum wire tunnel junctions. In Section 3, we discuss the simulation results. Finally in Section 4, we draw some conclusions from the present study.

2. Design procedure

The low tunneling behavior of lightly-doped p–n junctions encouraged us to consider an $Al_{0.3}Ga_{0.7}As$ p^{++}–n^{++} tunnel structure with 5×10^{19} cm^{-3}–3×10^{19} cm^{-3} doping concentration levels as a typical conventional tunnel junction (CTJ). This structure shows a peak tunneling current equal to 0.24 A/cm^2, which is suitable for tunnel junctions of commonly used multijunction solar cells under lower multiple of solar concentration

As explained, the tunneling performance of conventional p^{++}–n^{++} tunnel junction can be raised by introducing a quantum well structure between n- and p-type layers. However, the quantum well with doped barrier layers show higher influence than standard undoped quantum wells especially in the case of electron mobility.[13] According to this fact, our proposed quantum well tunnel junction (QWLTJ) is considered as a structure composed of an undoped GaAs layer sandwiched between two p^{++}- and n^{++}-AlGaAs barrier layers. Although the middle GaAs layer in QWLTJ with the lower energy band gap enhances the tunneling probability, the simulation results show that it does not increase the peak tunneling current considerably.

Using the low-dimensional structures provides a means to increase the peak current by reducing the effective band gap without increasing the absorption (loss) too much due to a reduced density of states.[6] Therefore, the quantum wire tunnel junction (QWRTJ) which can be experimentally produced by etching the undoped GaAs layer of quantum well structure can present a higher tunneling current. The width of and the gap between wires are considered to be 30nm which can be fabricated with new technologies.

Increasing the probability of tunneling, even increasing it up to a value much more than previous one, needs highly-degenerated structures. This is due to the fact that the conduction and valence band will be kept away from the Fermi level. To provide the mentioned high degeneracy, we make use of the delta-doping technique which is referred to as a doping distribution of semiconductors that is scaled down in one dimension to their ultimate spatial limits. It can be experimentally achieved by interrupting the crystal growth procedure and evaporation of dopants on the crystal surface.[14] The doping distribution of delta-doped structure which can be described with a two-dimensional δ-function, affects the local band gap. The conduction band energy of δ-function-like doping structure in the depth direction of z can be expressed as[11]

$$E_{\mathrm{C}}(z)=\begin{cases}-\dfrac{e^2N_D^{2D}}{2\varepsilon}(z-z_D) & \text{for } z\le z_D,\\ +\dfrac{e^2N_D^{2D}}{2\varepsilon}(z-z_D) & \text{for } z\ge z_D,\end{cases} \tag{1}$$

where e and ε are electron charge and permittivity; N_{d}^{2D} and z_D are the density and location of dopants on the z axis, respectively. The corresponding potential well is V-shaped and symmetric with respect to z_D.

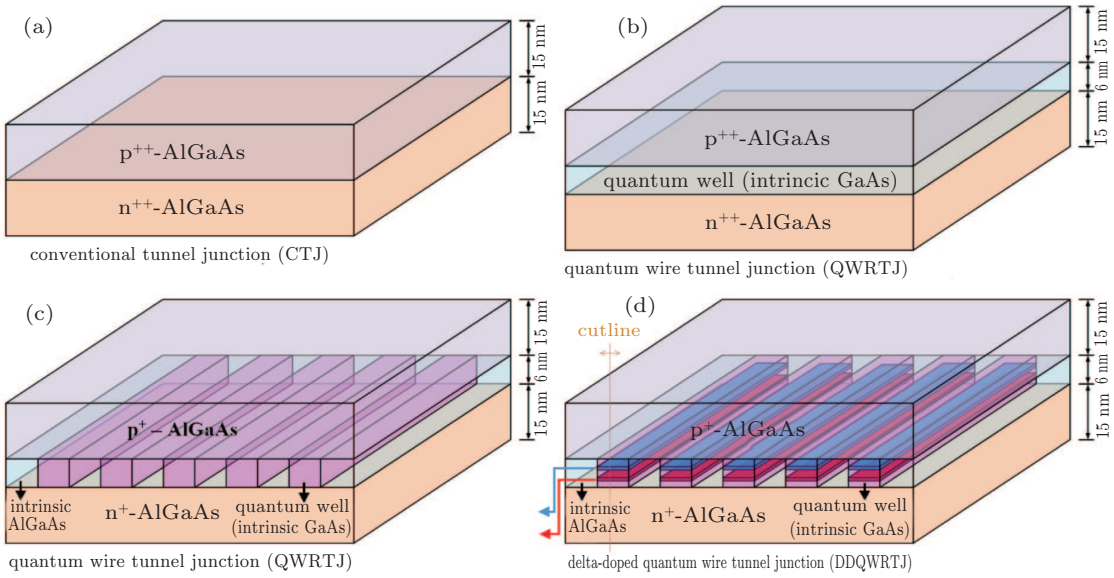


Fig. 1. Schematic diagram of (a) conventional, (b) quantum well, (c) quantum wire, and (d) proposed delta-doped quantum wire tunnel junction.

Equation (1) clearly shows the dropping of the conduction band from the Fermi level. The electron distribution in the well can be calculated by self-consistently solving Schrodinger and Poisson equation. For simultaneously taking the advantages of higher spatial confinement and high degeneracy, we propose a novel tunnel junction based on delta-doped quantum wires. The design process of our proposed tunnel junction is shown in Fig. 1.

Figure 1 illustrates the design procedure from a p^{++}–n^{++} $Al_{0.3}Ga_{0.7}As$ conventional tunnel junction (with doping concentrations of 5×10^{19} cm^{-3}–3×10^{19} cm^{-3}) to delta-doped quantum wire tunnel junction. Simulation results of the proposed structures will be presented in Section 3.

3. Simulation results and discussion

Firstly, we simulate an $Al_{0.3}Ga_{0.7}As$ CTJ with a $5\times10^{19}cm^{-3}$–3×10^{19} cm^{-3} doping concentration. However, to elevate the peak tunneling current, a quantum structure is utilized. Therefore, as can be seen in Fig. 1(b), a thin intrinsic GaAs layer is inserted between AlGaAs layers. As previously explained, the doped barrier layer makes the performance of quantum well structure better. The current–voltage characteristics of the conventional and quantum well tunnel junctions are depicted in Fig. 2.

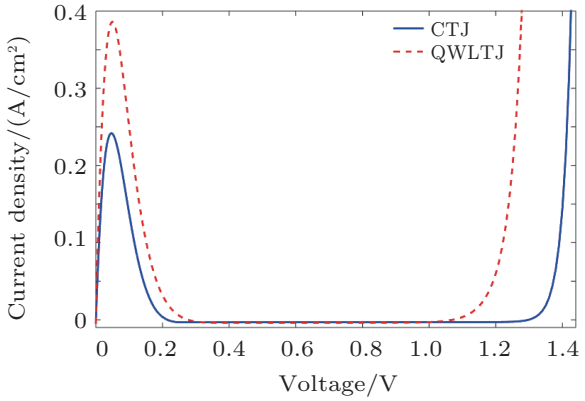


Fig. 2. The *I*–*V* characteristic curve of conventional and quantum well tunnel junction.

As can be seen in Fig. 2, although the peak tunneling current of quantum well tunnel junction is higher than that of the conventional structure, the highly concentrated solar cells require the tunnel junctions to be able to let the higher level current density to pass through.

It is obvious that the quantum wire structure, shown in Fig. 1(c), will improve the tunneling behavior in comparison with quantum well due to the higher quantum confinement. Also, the high degeneracies coming from delta-doping technique can extremely augment the peak tunneling current. Therefore, we present a novel delta-doped quantum wire tunnel junction (DDQWRTJ) as a highly degenerated multi-sub-band structure. As can be seen in Fig. 1(d), our proposed tunnel junction is composed of two 15-nm p^+ and n^+ $Al_{0.3}Ga_{0.7}As$ layers along with GaAs wires with two delta-doped regions. As previously mentioned, it is hard to fabricate a tunnel structure with a very high doping concentration of 5×10^{19} cm^{-3}. As a consequent, we are trying to introduce an enhanced tunnel junction which presents higher peak current in low doping concentration. For achieving a structure which can be easily fabricated, we reduce the doping concentration of p- and n-type AlGaAs layers in QWR and DDQWR structure to 3×10^{19} cm^{-3} and 1.5×10^{19} cm^{-3}, respectively. Two narrow 7.5 Å regions are delta-doped with two-dimensional sheet doping concentration of 3×10^{12} cm^{-2} between 1.5-nm spacer layers. The *I*–*V* characteristic curve of the proposed quantum wire tunnel junction and that of delta-doped quantum wire tunnel junction are compared in Fig. 3.

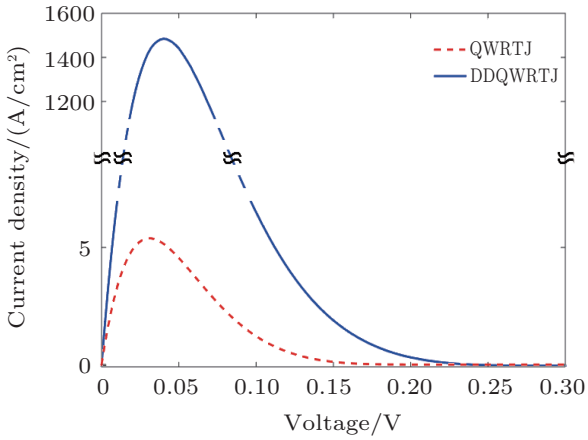


Fig. 3. The *I*–*V* characteristic curve of quantum wire and delta-doped quantum wire tunnel junction.

As shown in Fig. 3, although the performance of quantum wire tunnel junction is better than the those of previously discussed structures, the delta-doping of tunnel junction can extremely enhance the peak tunneling current.

For a multijunction solar cell with typical short circuit current of almost 15 mA/cm^2, the proposed structure with a peak tunneling current of 1480 A/cm^2 can be utilized as a tunnel junction with a highest possible solar concentration. Also, as can be understood, utilizing the proposed tunnel junction in a multijunction solar cell results in a voltage drop of 40mV which is drastically low. So, due to the high peak current, the resistance of tunneling region extremely decreases. It is obvious that the internal sub-band of quantum wire structure increases the number of energy levels that can be occupied by the electrons. However, the extraordinary difference between a structure with delta-doping and a structure without delta-doping is because of the increase of tunneling probability due to local band gap displacement. The energy band dia-

gram for a cutline shown in Fig. 1 for proposed DDQWRTJ is calculated and depicted in Fig. 4.

As shown in Fig. 4, a nanoscale two-dimensional delta-doping increases the effective doping concentration and displaces the corresponding conduction and valence bands. These local displacements of energy band diagram allow us to reach a very high tunneling probability with local shrinking of the band-to-band tunneling barrier. The effect of this local shrinking on the tunneling probability can be understood if the distance between electrons and holes for the delta-doped structure is comparable to simple quantum wire tunnel junctions' size.

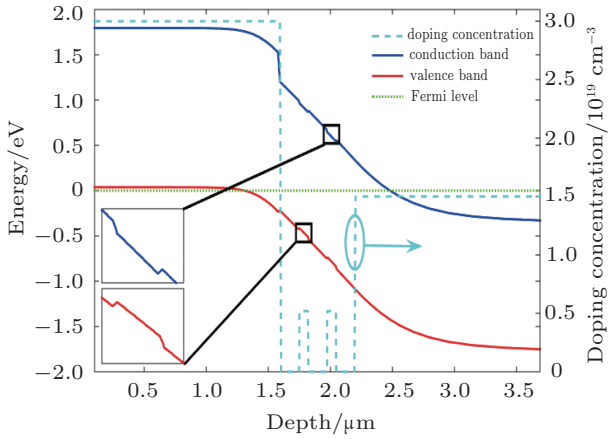


Fig. 4. Energy band diagram of a cutline of proposed DDQWR structure.

Simulation results show that the proposed structure presents the higher performance than the other counterparts even when the doping concentration of upper and lower AlGaAs layer are both reduced. Figure 5 shows the *I*–*V* curves of proposed DDQWRTJ for different doping concentrations of delta-doped or AlGaAs neighboring regions. Figure 5(a) shows the *I*–*V* curves of proposed structure for different sheet delta doping concentrations in the case of neighboring p–n AlGaAs with a constant doping concentration in a range of 2×10^{19} cm^{-3}–1.7×10^{19} cm^{-3}. Also, figure 5(b) shows the variations of *I*–*V* curve for different doping concentrations of neighboring region for a constant delta-doping concentration of 3×10^{12} cm^{-2}.

As can be seen in Fig. 5, although the very high current densities which guarantee that the solar concentrations higher than 4.6×10^4 times solar concentration are not applicable according to limitations about the highest possible solar concentration, the presented delta-doped quantum wire structure allows us to design the tunnel junctions with the capability of passing the tunneling current even higher than 1480 A/cm^2 in the case.

As previously mentioned, the proposed structure can be experimentally produced with 30-nm technology including deposition, photolithography and isotropic etching. It is worth noting that the performance of proposed device may be affected due to fabrication tolerance. In the case of our structure, there are two important parameters which can degrade the tunneling probability, *i.e.*, the variations of doping of delta-doped regions and width of quantum wires. The effect of the mentioned parameters on the peak tunneling current density of structure is shown in Fig. 6.

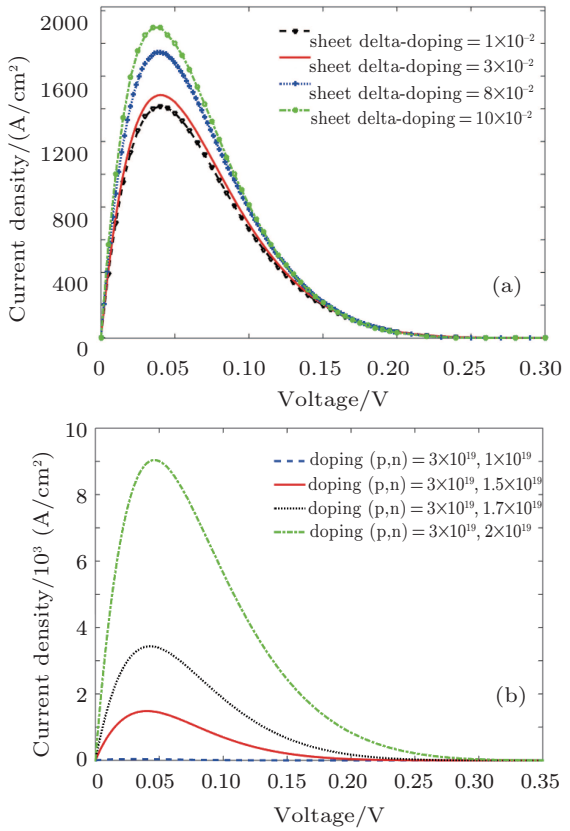


Fig. 5. The *I*–*V* curves of proposed DDQWRTJ (a) for different delta-doping concentrations (in the case of constant doping of 2×10^{19} cm^{-3}–1.7×10^{19} cm^{-3} for neighboring p–n AlGaAs); and (b) for different doping concentrations of upper and lower AlGaAs (in the case of 3×10^{12} cm^{-2} constant delta-doping).

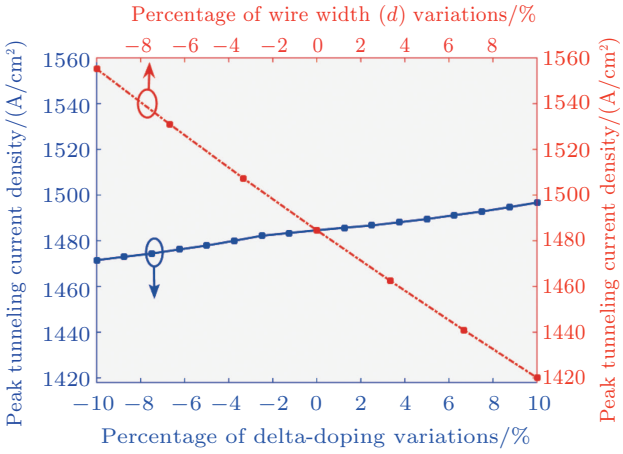


Fig. 6. Peak tunneling current density *versus* relative variations of delta-doping level (blue) and width of quantum wire (red).

The fabrication tolerance of the mentioned parameters is considered to be ±10%. As can be seen in Fig. 6, although the

variation of width of quantum wires changes the peak tunneling current density, even the lowest tunneling current can pass the current of highly-concentrated multijunction solar cells. Also, it is obvious that the variations of delta-doping cannot affect the performance of structure.

Finally, it can be understood that the two-dimensional sheet doping concentrations can be more reduced with employing a higher number of delta-doped regions in order to achieve the same tunneling current.

4. Conclusions

A novel delta-doped AlGaAs/GaAs quantum wire tunnel junction is proposed. The combination of quantum wire structure with delta-doped structure allows us to simultaneously have their corresponding advantages including higher quantum confinement and high degeneracy. The comparison of *I*–*V* characteristics between conventional and quantum well, and the comparison between quantum wire tunnel junction and delta-doped quantum wire tunnel junction show a considerable enhancement for the later ones (*i.e.*, for quantum well and delta-doped quantum wire tunnel junction). The proposed tunnel junction with a peak tunneling current of 1480 A/cm^2 can be utilized for the highest possible solar concentration.

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