Supporting information

Atomic-Monolayer Two-Dimensional Lateral Quasi-Heterojunction Bipolar Transistors with Resonant Tunneling Phenomenon

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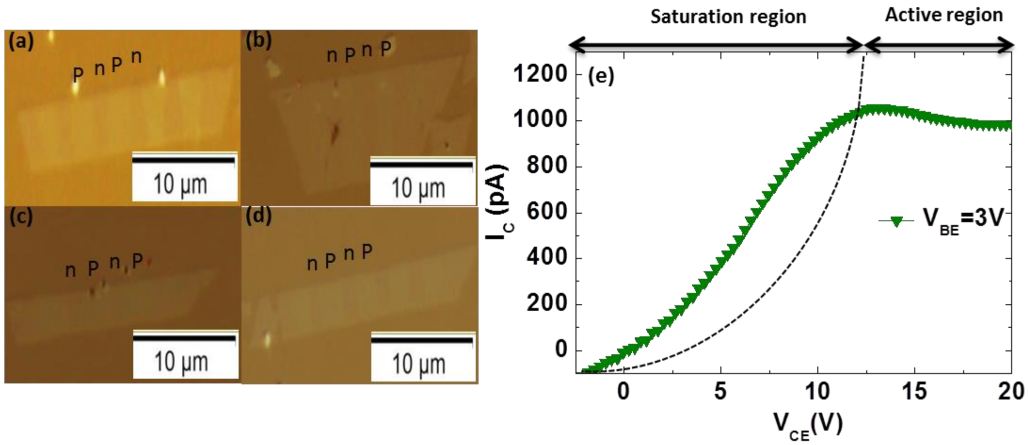


Supplementary Figure 1: Patterned ribbon images and electrical characteristic of two-dimensional lateral quasi-heterojunction bipolar transistors. (a) 、(b) 、(c) and (d) shows optical micrographs of different lateral heterostructure ribbons where *n*-type material and *p*-type material are MoS_2 and WSe_2, respectively. (e) General output characteristic of the lateral n-p-n quasi-heterojunction bipolar transistors, showing both saturation and active operation region.

Resonant tunneling mechanism

The fundamental energy band diagram with confined states in the situation of large base and collector bias voltages is proposed for illustrating the mechanism behind in Supplementary Figure 2.[1-4] Theoretically, the output features of resonant tunneling process is mainly determined from the part of the carriers from the emitter tunnel to the quantum well. The energies of first part can be expressed by:

$$E=E_c+h^2k_{\perp}^2/2m^*+h^2k_{\parallel}^2/2m^* \quad (1)$$

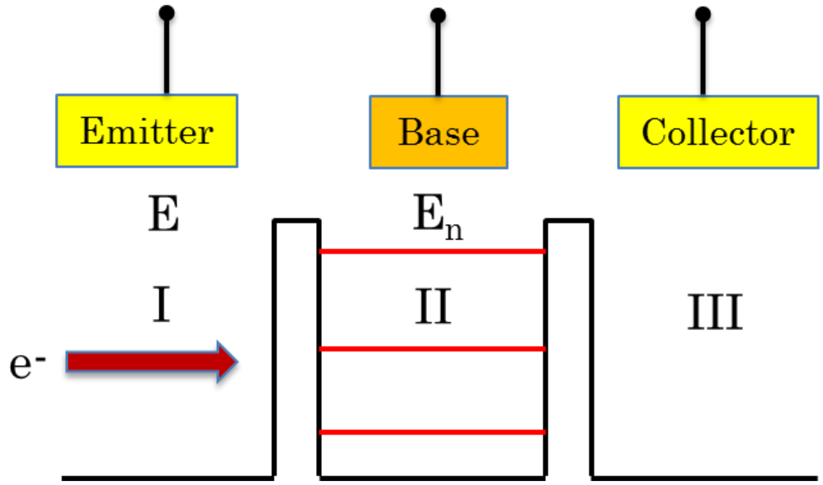
where E_c is the bottom edge of the conduction band, h is the Planck constant, $k_{\perp}$ is the momentum of the perpendicular to the tunnel direction, m^* is the effective mass, and $k_{\parallel}$ is the momentum of the parallel to the tunnel direction. The second part which is energies in the well is limited at horizontal direction due to the barriers. This can be expressed by :

$$E_W=E_n+h^2k_{\perp}^2/2m^* \quad (2)$$

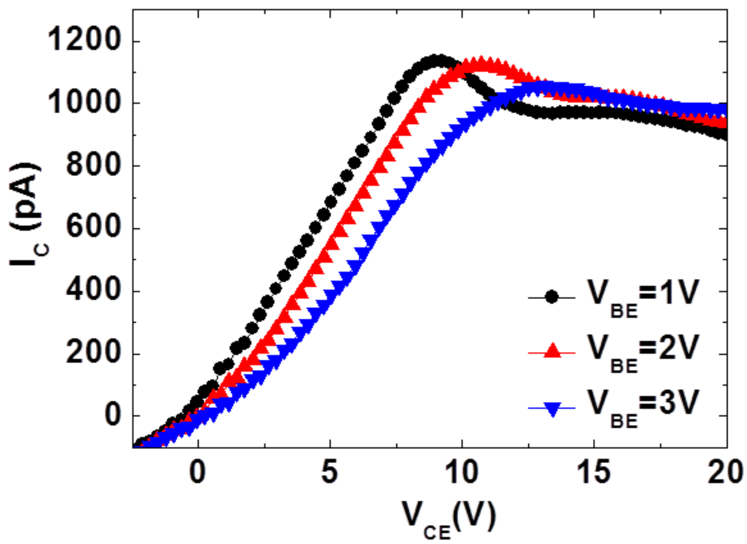
where E_W is the energy of the quantum well and E_n is the quantization of energy level at quantum well. Among which, the continuous band is decomposed into discrete energy levels, forming the discrete energy and standing wave. If it is conforming to the law of conservation of energy, when the first part energies are aligned to the second part energies, the equation (1) should be equal to the equation (2), and the quantization of energy level at quantum well should be complied with the expression:

$$E_n=E_c+h^2k_{\parallel}^2/2m^* \quad (3)$$

Accordingly, when E_n is larger than E_c, the resonant tunneling effect would be happened.



Supplementary Figure 2. Schematic plot of a resonant tunneling mechanism model. The emitter, base and collector region are the part I, part II and part III respectively. The confined states are formed in the situation of large base and collector bias voltages applied. The electrons tunnel from part I to part III due to the alignment with quantum state. The red line is the confined state and En is the quantization of energy level at quantum well.



Supplementary Figure 3: Output characteristic in another lateral n-p-n quasi-heterojunction bipolar transistor, showing the similar negative differential resistance phenomenon.

Estimation of energy states and Fermi level tuning for the resonant tunneling phenomenon in a n-p-n lateral quasi-heterojunction bipolar transistor

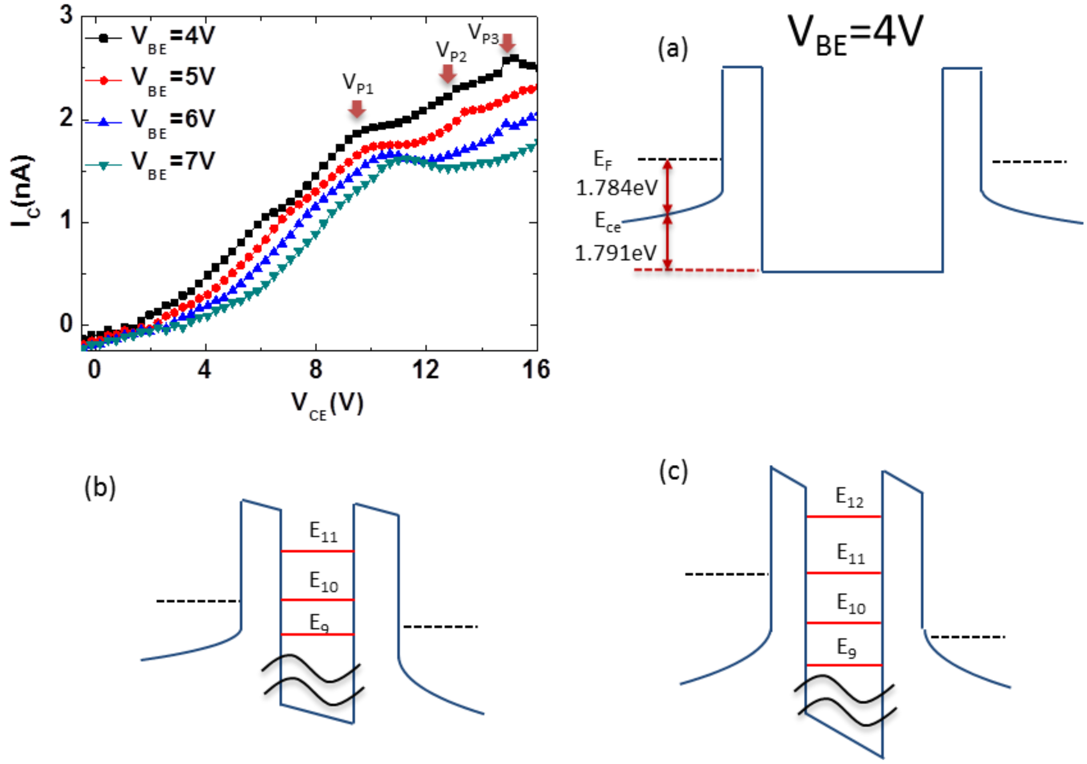
According to our estimation of depletion layer (1.2964μm) in the main text, the corresponding well width is about 3.6nm while the base width is experimentally observed to be about 1.3μm. With this value of well width, the aligned energies of the confined states can be thus estimated by equation (4).

$$E_n=n^2h^2/8m^*L^2 \tag{4}$$

where L is the well width, n is the confined state number. Hence, the potential energy states for the alignment are determined to be E_{10}=6.4eV, E_{11}=7.8eV, E_{12}=9.288eV, E_{13}=10.9eV and E_{14}=12.64eV. Based on band diagram in Figure 3(d), we know that the band gap difference between emitter and base is 2.209eV(2.46eV-0.216eV-0.035eV). For the case of applying base bias of 4V, the edge of the base conduction band were lower 1.791eV than that of the emitter and the E_F is about 1.784eV higher than E_{ce} as shown in SF4(a). Under this condition, the V_{CE} must increase to 8.46V (corresponding to V_F=-4.46V) and then the quantum wells that attain by applying bias voltages would be formed. Once quantum well is formed, the corresponding tunneling peak voltage (position) can be approximately determined by: [5]

$$V_P \doteq 2(E_n-E_{ce})/q \tag{5}$$

where V_P is tunneling peak voltage, E_{ce} is the bottom edge of the emitter conduction band, q is the unit electron charge. Accordingly, first tunneling peak (V_{P1}) is about 9.2V while the Fermi level aligns with E_{10}. This peak position is exactly located in the experimental observation as shown in SF4. In succession, the second tunneling peak V_{P2} is about 12V and the third tunneling peak V_{P3} is about 15V due to the alignment with E_{11} and E_{12} respectively. The corresponding schematic energy band diagrams for E_{10} and E_{11} are shown in SF4(b) and (c). We intentionally mark the estimated peak positions to match the observed resonant peaks in SF4. However, some of resonant peaks are not evident. We think it is due to the fact that thermal broadening and fluctuations exist in room temperature when high bias voltages are applied.



Supplementary Figure 4. Energy band diagrams for the illustration of energy states and Fermi level tuning for the resonant tunneling phenomenon in a n-p-n lateral quasi-heterojunction bipolar transistor. The example is that when V_{BE}=4V.

References

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