Physica E 6 (2000) 331–334

PHYSICA E

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A light-induced tunneling state in a submicron double barrier tunneling diode with a center-doped well

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Abstract

We will present the observation of a light-induced meta-stable impurity state in a submicron center-doped double barrier tunneling diode (DBRTD) manufactured by a novel single-step e-beam lithography process in which no further alignment for the interconnect between the bonding pad and the small active device region is required. We attribute the meta-stable tunneling state, which can be switched by light and high voltage bias, to the light- or field-induced charge redistribution in the active tunneling region. © 2000 Elsevier Science B.V. All rights reserved.

PACS: 73.02.Hb; 73.23.−b; 73.40.Gk; 73.40.Kp; 73.61.Ey; 73.50.Jt

Keywords: Double barrier tunneling diode; Magnetic field; Impurity state

Study on the double-barrier resonant tunneling diodes (RTDs) with intentionally doped donor impurities between the barriers has revealed additional features related to tunneling through the localized impurity levels at bias lower than that of the conventional tunneling through the quasi-two-dimensional (2D) states in the well [1]. Further lateral confinement of the device size down to submicron-scale perpendicular to the tunneling direction allows us to investigate the electronic energy levels in the few-impurity or even single-impurity system in a quantum box [2–4]. In this paper we will present the observation of a light-induced meta-stable tunneling state in a submicron center-doped double barrier tunneling diode (DBRTD) manufactured by a novel single-step e-beam lithography process in which no further alignment for the interconnect between the bonding pad and the small active device region is required. We attribute this meta-stable state which can be switched by light and high voltage bias to the light- or field-induced charge redistribution in the active tunneling region.

The MBE layer structure of the DBRTD mainly consists of a 10 nm GaAs quantum well (QW) with a 3×10^{10} cm^{-2} Si doping layer in the center, flanked with a 4 nm AlAs barrier on both sides, set back

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PII: S1386-9477(99)00166-6

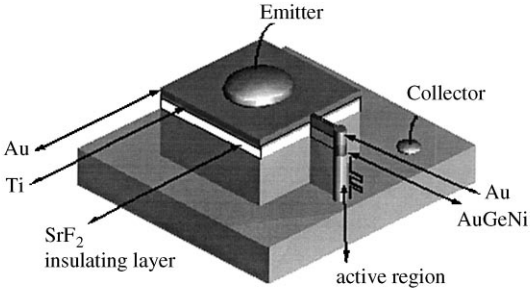

Fig. 1. Schematic diagram of the device structure.

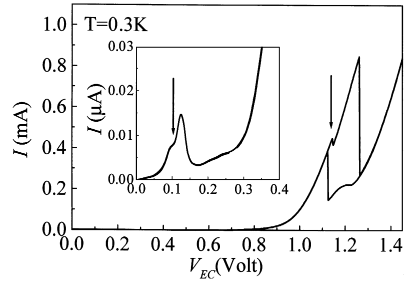

Fig. 2. The *I–V* characteristics of a 0.5 μm-diameter DBRTD with 3×10^{10} cm^{-2} Si doping layer in the center of the QW.

from the n^+-type emitter and collector regions by a 10 nm and a 50 nm undoped spacer layers, respectively. A schematic representation of the device structure is shown in Fig. 1. An evaporated Au/Ti bonding pad separated from the semiconductor surface by an insulating layer (SrF_2) is first formed. The active device area, a 0.5 μm-diameter dot with a 0.2 μm-wide long tail connected to the bonding pad, is defined by a single e-beam writing process on the standard spin-on PMMA resist. The ohmic contact is formed by thermally depositing a 200 nm Au/Ge/Ni layer followed by a lift-off, a wet mesa etching, and an annealing process, consecutively. The region under the narrow long tail is completely depleted or etched through, and thus the only possible tunneling path is through the dot-shaped region. We have examined the *I–V* characteristics of the connecting wires of 0.3 and 0.2 μm widths without the dot. The 0.3 μm wide wire exhibits a tunneling diode behavior while the 0.2 μm one shows only a very low leakage current ($\lesssim$1 pA) much lower than the tunneling current in the whole experimental bias range. The actual diameter of the device is about 0.3 μm, i.e. 0.2 μm smaller than the nominal metal size due to undercut and edge depletion. The main advantage of this single-e-beam process technique is simple and straightforward compared to other techniques [5–13]. The only drawback is the high resistance of the narrow long connecting wire (about few kΩ), which can be overcome by using multiple wires connected to the active dot. We can even arrange a metal ring around the dot to form a remote control gate to tune the diode in the same e-beam writing process. Details of the device processing will be reported elsewhere [14].

The *I–V* characteristics in Fig. 2 for positive emitter to collector voltage (V_{EC}) at 0.3 K shows the first tunneling peak at 0.12 V with a shoulder near 0.1 V, and the second peak is at about 1.26 V (on the sweeping-up curve) with a small satellite peak at 1.15 V. For such a bias condition, the electron actually tunnels from the collector to the emitter, i.e. the device operates in a reversed mode. The small peaks below the main tunneling peaks become weaker upon applying high magnetic fields (B) in the direction of tunneling current while the main peaks do not, indicating that these features come from the localized impurity levels in the QW instead of extended 2D levels [1].

After illumination by a GaAs infrared LED near the sample at low temperature, we find an extra peak at the high-bias side of the first tunneling peak. More interestingly, if the applied bias exceeds 0.35 V, this light-induced peak will vanish and the *I–V* curve shape will be reset to the one before illumination as shown in Figs. 3(a) and (b). However, we notice a negative voltage shift of the tunneling *I–V* curve, indicating that a certain amount of negative charge is removed from the active tunneling region, including two AlAs barriers, QW in between and the undoped spacer next to top emitter. Fig. 3(c) shows the original curve (solid line labeled as I) before illumination, the one (solid circle line labeled as II) right after illumination and the one (dash line labeled as III) obtained after applying a high bias voltage together for comparison. The *I–V* curves II and III can be repeatedly switched back and forth by illumination and high electric fields.

To investigate the origin of the light-induced extra features in the *I–V* curve, we also study the evolution

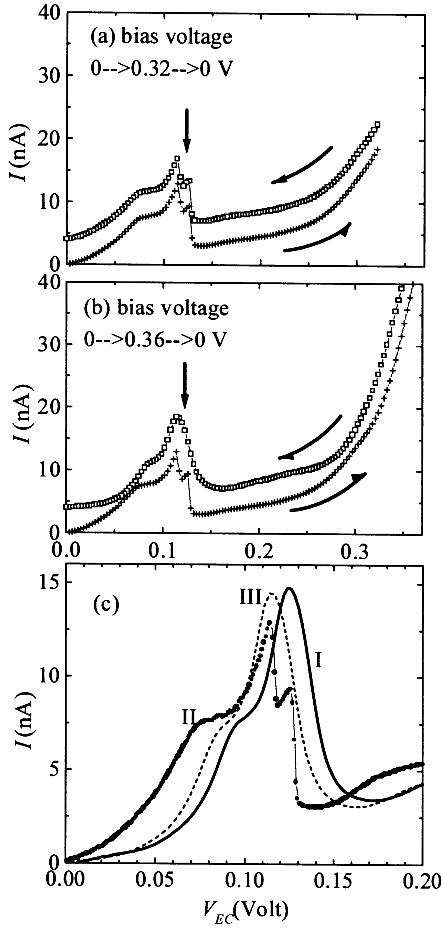

Fig. 3. The I–V characteristics right after LED illumination: (a) with bias applied less than 0.35 V, (b) with bias applied exceeding 0.35 V. The sweeping-down curve is offset by 4 nA for clarity. (c) The original curve I before illumination, curve II right after illumination and curve III obtained after applying a high bias voltage.

of these peaks as a function of B parallel to tunneling current. As shown in Fig. 4, at high B the main tunneling peak survives and becomes stronger with a slightly positive shift on the peak position while the additional peak at 0.13 V disappears similar to the peak associated with impurity level near 0.085 V. The origin of the additional peak is very possibly related to the impurities in the well. We have measured similar devices without the doping layer in the QW and no similar behavior was found.

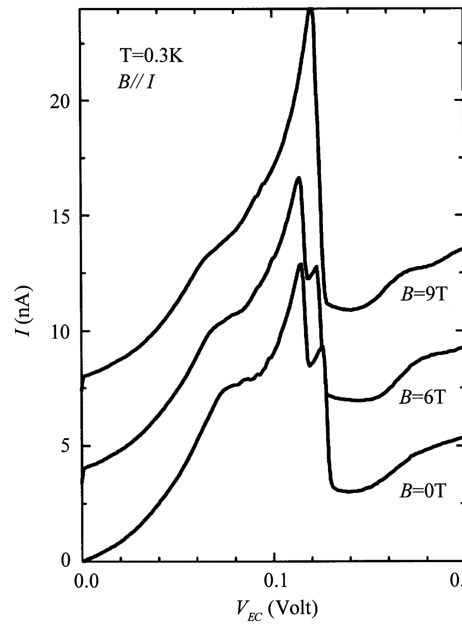

Fig. 4. The I–V characteristics right after illumination at low bias for $B = 0, 6$, and 9 T. The offset between two adjacent curves is 4 nA.

The width of the QW is 10 nm, very close to the effective Bohr radius a_B^* of a hydrogen-like impurity in bulk GaAs. The average spacing between Si-impurities is about 60 nm, much larger than a_B^*. The 0.3 μm effective device area contains about 85 Si impurities in the well. The shape of the wave function and the energy level of the electron bonded to the impurity ion are very sensitive to the charged impurities in the barriers, which can cause dramatic change in the boundary conditions. A negative charge trapped in the barrier will effectively increase the barrier height, which may raise the energy level nearby and also reduce the tunneling probability. A positive charge in the barrier will have the opposite effect. Not only the positions but also the shape of the I–V curve II in Fig. 3(c) is very different from the original curve I, indicating that the potential distribution near the tunneling barrier is seriously modified. Thus, part of the electrons removed by illumination must reside originally near the AlAs tunneling barriers, probably trapped by background acceptor impurities. The shape of the tunneling curve III after applying high enough electric fields restores to its original form but with a residual negative shift of about 10 mV in the peak position which has to do with the trapped electrons removed by light but not recovered by electric field in the spacer layer. These electrons can originally be trapped by deep levels within the band gap. The charge distribution in the spacer, contrary to those near the tunneling barriers, will give only an energy shift to all the tunneling levels and will not effect the other tunneling properties. We can estimate the density of the impurities in the spacer from the voltage shift. A sheet of 2.7×10^{10} cm^{-2} impurities from the center of the 10 nm spacer layers (equivalent to 2.7×10^{16} cm^{-3} 3D density, which is reasonable considering the 1×10^{18} cm^{-3} doping contact region and heavy compensation of bulk doping), about 23 nm away from the electron-accumulating layer near the lower contact, will give about right voltage shift.

The origin of the tunneling state associated with the light-induced peak near 0.13 V on curve II in Fig. 3(c) is still not very clear. It may relate to light-induced lateral inhomogeneity due to different charging condition of the Si impurity layer in the well. The extra satellite peak is about 12 mV higher than the main peak, which is equivalent to an electrostatic potential shift of 3.9 mV near the center of the well, very close to the shift of 4.4 mV if we move all the electrons from the 3×10^{10} cm^{-2} impurity layer to the accumulation layer.

In conclusion, we have successfully used a novel single-step e-beam lithography to manufacture submicron-sized tunneling devices. We have observed a meta-stable tunneling state which can be switched by light and high voltage bias in a DBRTD of 0.3 μm diameter with a Si doping layer between tunneling barriers and attribute them to the light- or field-induced charge redistribution in the active tunneling region.

Acknowledgements

This work was supported by the National Science Council of the Republic of China through Grant No. of NSC88-2112-M-005-003.

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