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A Tristate Switch Using Triangular Barriers

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We demonstrate a new GaAs regenerative switching device with a double triangular barrier (DTB) structure, i.e., p^+-i-$\delta(n^+)$-i-$\delta(p^+)$-i-n^+, prepared by molecular beam epitaxy (MBE). Using the concept of sequential collapse of the internal barriers, two distinctive switching regions are established. First, a negative resistance region (S-type) is observed, followed by a positive resistance region (inverted N-shape) in between the switching behavior with the increase of applied bias. This device may have applicability for tristate logic circuits.

KEYWORDS: double triangular barrier (DTB), thermionic emission, quasi-on state

§1. Introduction

Recently, GaAs regenerative switches using bulk barrier structures have drawn great interest in high-speed applications.[1-7] The switching mechanism is due to the injected minority carrier accumulated at the internal bulk barrier to lower the effective barrier height by positive feedback. A negative resistance region is then observed between the low- and high-resistance regions.[1-4] We here describe a structure using the concept of two different types of bulk barriers to control the sequence of collapse for these barriers. An interesting switching behavior with an intermediate state is then demonstrated. This unique feature cannot be attributed to the oscillation of the biased circuit.[8]

For the proposed structure of p^+-i-$\delta(n^+)$-i-$\delta(p^+)$-i-n^+ grown by MBE, $\delta(n^+)$ and $\delta(p^+)$ indicate heavily doped thin layers with the thickness of 100 Å. Compared to the previous structures,[4,9] note the key role of $\delta(n^+)$ in forming the inverted triangular barrier. The fully depleted internal bulk barriers dominate the current transport in the device. Electrons and holes are then transported by thermionic emission as a unipolar triangular diode, while minority-carrier diffusion is not significant, as discussed previously.[1,3,10]

§2. Experimental

The cross section of the MBE-grown novel GaAs DTB switch is schematically shown in Fig. 1. Compared to the p^+-i-$\delta(p^+)$-i-n^+ structure of previous work,[4,9] the major difference is the insertion of the $\delta(n^+)$ layer in the i-region to form the inverted triangular barrier. Two undoped layers (p type) have the background concentration of about 10^{14} cm^{-3}. Silicon and beryllium were used as the n- and p-type dopants, respectively. GaAs epitaxial layers were grown sequentially on the (100)-oriented Si-doped GaAs substrate at 580°C, and the growth rate was 1 μm/h.[11] The corresponding layer thickness and doping concentration are illustrated in Fig. 1. The thicknesses for $\delta(p^+)$ and $\delta(n^+)$ are all 100 Å, while the doping concentrations are 5×10^{18} cm^{-3} and 1×10^{18} cm^{-3}, respectively. AuZn was evaporated and sintered to facilitate the ohmic contact of the p^+ layer, while AuGe was used for the n^+-substrate. The device is etched by $NH_4OH:H_2O_2:60H_2O$ solution, and the device area is about 10^{-3} cm^2.

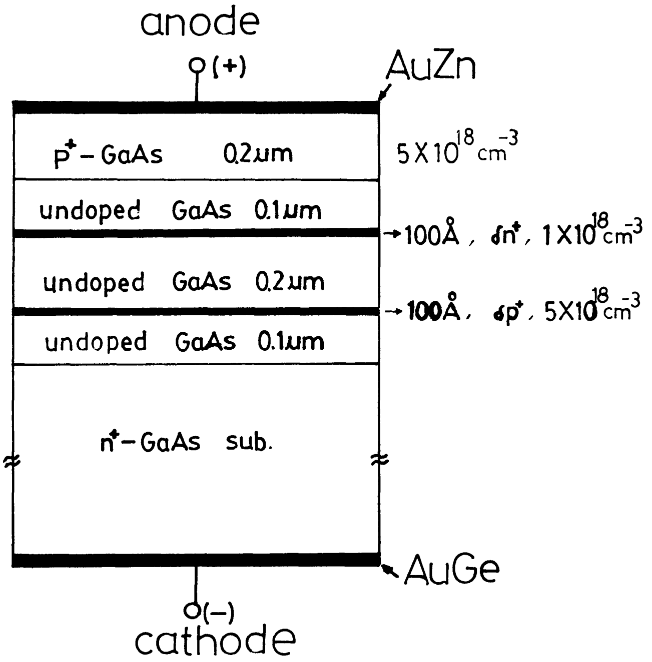


Fig. 1. The cross-sectional view of the proposed DTB switch.

§3. Results and Discussion

The typical current-voltage characteristics for the novel DTB switch are shown in Fig. 2. The switching sequence is indicated as 0→a→b→c→d→e with increasing applied anode to cathode bias (V_{AK}). When the device is turned off, the current changes with decreasing V_{AK} bias as e→d→c→b→a→0. Three states are clearly observed in the I-V characteristics and can be reproducible. First, an S-type switch is illustrated with switching voltage (V_S), and holding voltage (V_{h1}) referred to as the "quasi-on"

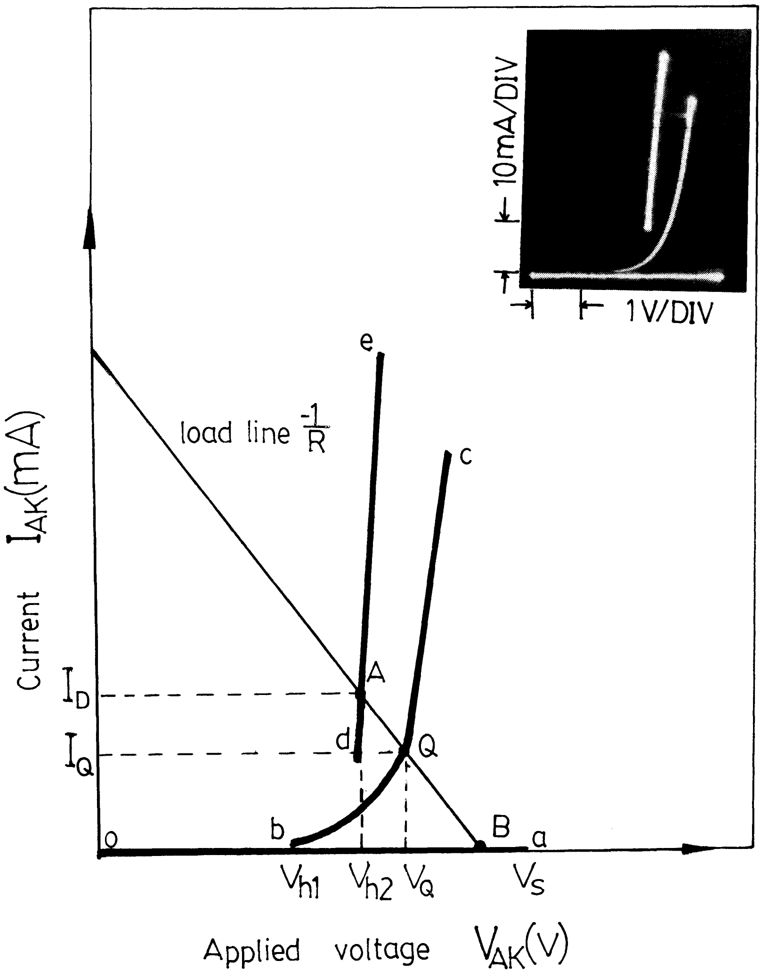


Fig. 2. The typical *I-V* characteristics of the DTB switch. The related device parameters are also shown.

state. There exists a negative resistance region between the high- and low-resistance states, similar to that of the switch reported previously.[2,4,9] With the increase of applied bias, another switching behavior is observed. It is noted that the resistance between the switching region is positive. This is the so-called inverted N-shape region, corresponding to the "on state". The corresponding holding voltage, V_{h2}, is larger than V_{h1}. This will be discussed later.

Another sample was measured on a different current scale to probe the device performance more clearly. The typical S-type characteristics (from the off state to quasi-on state) are shown in Fig. 3(a). The vertical current is 0.5 mA/div on the left while it is 10 mA/div on the right. The corresponding V_s, V_{h1}, I_S and I_{h1} are 3.6 V, 2 V, 0.2 mA and 1 mA, respectively, where I_{h1} (I_S) is the current at the bias of V_{h1} (V_S). The large quasi-on resistance is due to the p^+ ohmic contact and can be improved. In the intermediate state (quasi-on state), the applied bias in Fig. 2 is lower than that in Fig. 3. It may be attributed to the contact and external series resistance. As the applied V_{AK} bias is increased, another switching behavior is indicated in Fig. 3(b). An intermediate state is observed which cannot be attributed to the circuit oscillation.[8,9] The switch changes from the quasi-on state to the on state. The corresponding holding voltage (V_{h2}), 2.7 V, is larger than V_{h1} (2 V).

Based on a model established by the current equation and the continuity equation, the current-voltage characteristics are then calculated for the typical p^+-i-$\delta(p^+)$-i-n^+ regenerative structure.[3] No such tristate switching behavior is observed. Replacing the i-layer by n or $\delta(n^+)$ of the p^+-i-$\delta(p^+)$ structure, there is no switching behavior; the structure behaves as a forward biased diode only. The introduced $\delta(n^+)$ layer therefore plays the key role in the existence of such switching behavior.

The mechanisms accounting for the key features observed in the experiment are qualitatively described as follows, with the help of the band diagram shown in Fig. 4. It is well known that the major contributing current for bulk barrier devices is the thermionic emission current at room temperature. One can predict that both the electron and hole currents across the internal barrier are due to thermionic emission, but not minority carrier diffusion. However, we do not exclude the possible minor role of the minority carrier diffusion operating on the conventional regenerative switches.[1-3]

For the off state with the applied positive V_{AK} bias, the voltage across the barrier is illustrated in Fig. 4(a) as $V_{AK} = V_1 + V_2 + V_3$. The barrier heights for ϕ_{b1} and ϕ_{b2} are high,[2] and corresponds to $d_1 d_2 Q_i / [(d_1 + d_2)\varepsilon_s]$, where Q_i is the area density of ionized acceptors or donors in the barrier layer, and d_1 and d_2 are the thicknesses beside the internal barrier layers,[12] so that thermionic emission elec-

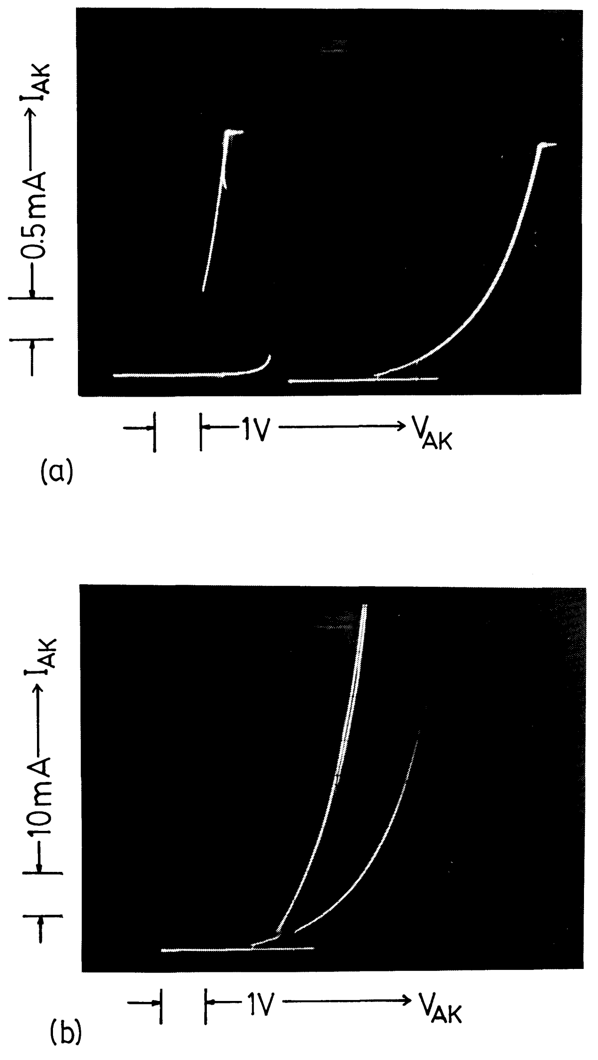
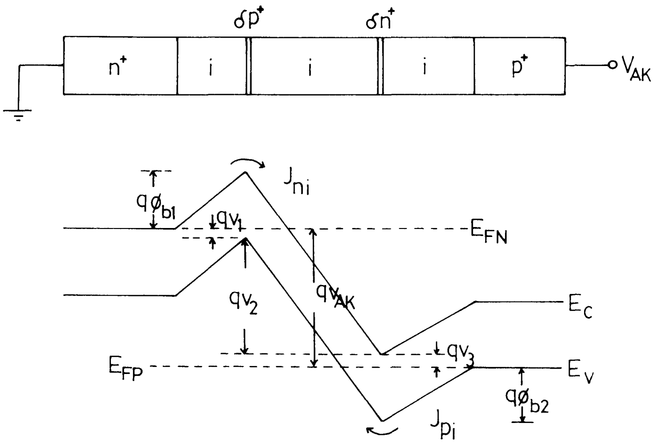
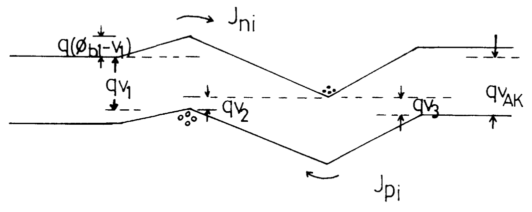


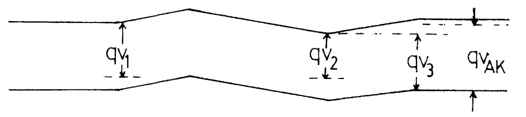
Fig. 3. (a) The switching characteristics for the quasi-on state. The two curves are the same shape but measured on a different current scale. The vertical current is 0.5 mA/div on the left while it is 10 mA/div on the right. (b) The overall switching behavior.



(a) OFF state



(b) Quasi-ON state



(c) ON state

Fig. 4. The band diagram for the DTB switch: (a) off state, (b) quasi-on state, and (c) on state.

trons and holes are very small; i.e., only very small current flows in the device which indicates a high-impedance state. Thus, it is reasonable to assume $\phi_{b1} > \phi_{b2}$ due to the larger doping concentration of the $\delta(p^+)$ layer. The thermionic hole current is then larger than the electron current. This concept will render the collapse of $\delta(p^+)$ and $\delta(n^+)$ barriers sequential, not simultaneous. Holes accumulated at the $\delta(p^+)$ barrier increase with increasing applied bias. At the critical bias, V_S, the number of holes accumulated at the $\delta(p^+)$ barrier is large enough to reduce the barrier height effectively; then, a large number of electrons will be emitted thermonically over the barrier. This implies the collapse of the $\delta(p^+)$ barrier corresponding to the quasi-on state of the band diagram shown in Fig. 4(b). The holding voltage, 2 V, is reasonable for the sum of the voltage across the internal barrier and the voltage due to the series and contact resistance. Compared with the band diagram of the off state, V_1 and V_3 increase, especially V_1, while V_2 changes from reverse bias to forward bias.

With futher increasing V_{AK} bias, I_{AK} increases. The injected electrons from the i-$\delta(p^+)$-i collapsed barrier which have accumulated at the i-$\delta(n^+)$-i barrier increase, which will effectively lower the i-$\delta(n^+)$-i barrier. For a certain level of anode-to-cathode current (I_{AK}), the established positive feedback enables the collapse of the $\delta(n^+)$ barrier. Another switching behavior is indicated, corresponding to the on state. There exists a positive resistance region with inverted N-shape switching characteristics, between the quasi-on state and on state. The band diagram for the on state is illustrated in Fig. 4(c). Compared with Figs. 4(b) and 4(c), it indicates clearly why $V_{h1} < V_{h2}$. For the on state, V_1 increases with increasing emitted electrons due to the barrier lowering. The accumulated electrons at the internal i-$\delta(n^+)$-i barrier also lower the barrier height effectively which increases V_3. V_2 also increases, and $V_{h2} = V_1 + V_2 + V_3$ then increases. The indicated value is almost equal to the GaAs energy gap, which is smaller than the experimental results. The difference is attributed to the existence of the series and contact resistance, which can be improved. At this bias, the total emitted electron and hole currents are larger than the case of the quasi-on state, so that I_{h2} is larger than I_{h1}.

When $V_{AK} < 0$, the current-voltage characteristics are similar to those of a p-n junction. No switching behavior is observed. With a suitable operating point, Q, located at the quasi-on state as the load line shown in Fig. 2, a tristate logic operation may be possible.

§4. Conclusions

A novel GaAs switch (DTB) using two triangular barriers of opposite type prepared by MBE is demonstrated. The interesting switching performance is discussed as the sequential collapse of the internal barriers. Due to the sequential collapse of the internal barriers, an intermediate state (quasi-on state), which is investigated for the first time, is produced. In other words, because the two internal barrier heights are not equal, the *I-V* characteristics can be regarded as two switching phenomena. The first switching route in the *I-V* curve (0→a→b) is dominated by the $\delta(p^+)$ barrier drop when the external bias is applied. But the second switching route (b→c→d→e) is due to the collapse of the $\delta(n^+)$ barrier. Applications for such a new device are under development.

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