Electric properties of unipolar GaAs structures with ultrathin triangular barriers

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Unipolar GaAs structures with built-in planar-doped triangular barriers (*n-i-p*$^+$*-i-n*) have been investigated experimentally. Current-voltage characteristics of ultrathin (400 Å on each side) barriers have been measured at temperatures ranging from 77 to 450 K. It is found that the characteristic activation energy E_a for current of both polarities strongly depends on temperature, changing from 1.05 eV at room temperature to 0.4 eV at 77 K. Such variation of the activation energy is interpreted as a transition from the thermionic mechanism of current to thermally assisted tunneling.

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In the present letter we report results of our experimental study of unipolar GaAs structures with ultrathin triangular barriers (TB). Rectifying diodes based on TB structures have been recently fabricated by molecular beam epitaxy using either variable-gap semiconductor alloys[1] (GaAlAs with varying aluminum content) or modulation doping in GaAs (Ref. 2) (planar-doped *n-i-p*$^+$*-i-n* structure). In these diodes the current is due to charge injection.[3] The TB structures of planar-doped type have been used as an element of a photodetector,[4] a hot-electron transistor,[5] and a two-terminal switching device.[6] Devices utilizing triangular barriers have been also proposed in Ref. 7 (transistor based on gate-controlled thermionic emission) and Ref. 8 (a transit-time device of barrier injection type).

The nature of the current in TB diodes is quite similar to that in a forward-biased Schottky diode. At room temperature the current is mainly thermionic, whereas at lower temperatures the favored mechanisms are those which require smaller activation energy. For Schottky diodes one such mechanism is the thermionic field emission or thermally assisted tunneling.[9] In the present work we find that for TB diodes with ultrathin barriers the current at low temperatures also becomes nonthermionic, as is manifested by a different activation energy.

The experimental structure, shown schematically in Fig. 1 (insert) was grown by MBE on a Si-doped *n*-type GaAs substrate of (100) crystal orientation. Growth took place under arsenic-rich conditions at a substrate temperature of 645 °C and produced smooth featureless surfaces. The first n^+ layer was 1.9 μm and the upper n^+ layer was 0.5 μm thick. The n^+ layers were doped with silicon to a carrier concentration of 2×10^{18} cm^{-3} and the p^+ layer was doped with beryllium at a level equivalent to that which would produce a bulk carrier concentration of 2×10^{18} cm^{-3}. The *i* layers were grown without exposure to any dopant oven beams, which produced *n*-type background concentration of 10^{15}–10^{16} cm^{-3} in calibration runs.

From grown epitaxial layers test diodes were fabricated in the following way. Circular dots of diameter varying from 250 to 50 μm were defined by conventional photolithography using a silicon nitride mask. Contacts were first formed by AuSn electroplating, alloyed in H_2 ambient for 15 s at 450 °C, and then overplated with pure gold. After removing the nitride mask with plasma etching, circular mesas were finally formed by chemical etching down to n^+ substrate with 1:1:3 solution of sulphuric acid and hydrogen peroxide in water. To minimize series resistance devices were bonded in standard IC package.

The current-voltage characteristics were measured over 11 decades of current using Keithley logarithmic ammeters at low currents. Measurements were made at temperatures ranging from 77 to 450 K.

Some of the measured *I-V* characteristics are displayed in Fig. 1. At low currents the dependence on voltage is strictly exponential for both polarities of the applied voltage, whereas at higher currents the exponential dependence saturates. Mechanisms of this saturation and the eventual replacement of the exponential *I-V* characteristic by a linear law have been discussed in detail in Ref. 7. This effect is not peculiar to ultrathin barriers and it has been observed in TB diodes of varying barrier thickness.[10] At high currents all curves corresponding to the direction of electron flow from the substrate and towards the surface exhibit a sharp upturn,

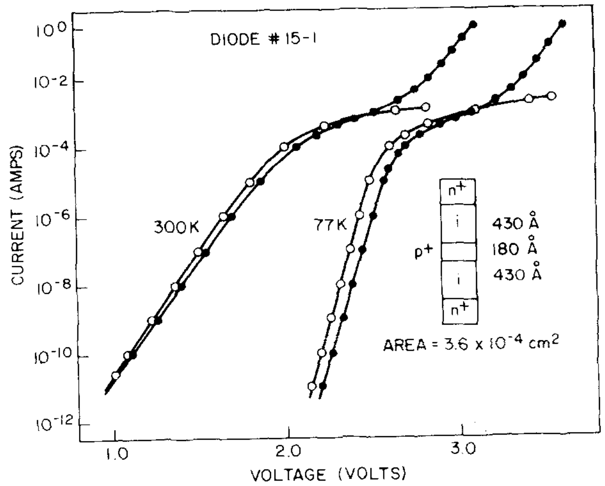

FIG. 1 Current-voltage characteristics of thin TB diodes at 300 and 77 K. Solid dots and open circles correspond to the positive polarity applied to the surface and the substrate, respectively.

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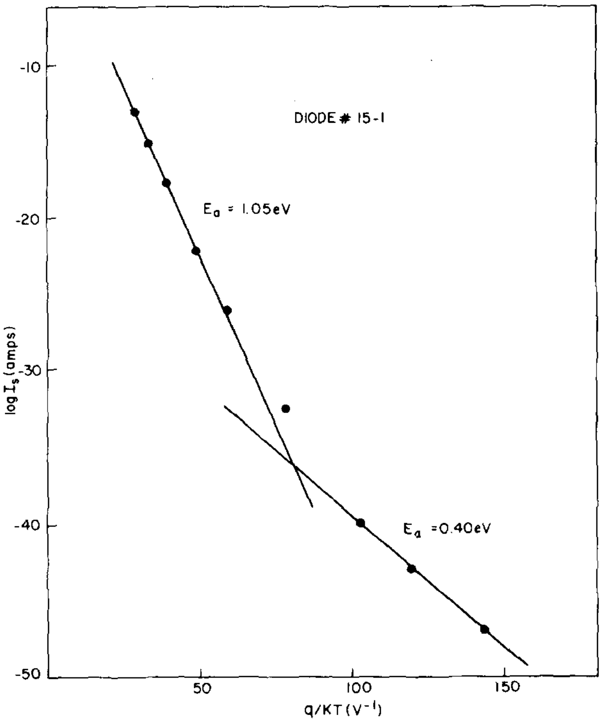

FIG. 2. Temperature dependence of the current extrapolated to zero voltage.

i.e., these curves become again exponential. The slope of this "second exponent" is independent of temperature. This phenomenon, which is probably associated with tunneling of holes, is not completely understood and requires further study.

Curves of both polarities extrapolated to $V = 0$ meet at the same point for any given temperature. The extrapolated value of the current I_s itself depends on temperature, and the dependence $\log I_s$ vs $1/T$ is plotted in Fig. 2. The slope of this dependence determines the activation energy E_a of the dominant mechanism of the current. From Fig. 2 it is seen that E_a is markedly different at high and low temperatures. At high temperatures the current mechanism is undoubtedly thermionic and the activation energy $E_a = 1.05$ eV should be identified with the barrier height. This is close to the 1.05 V of the potential drop anticipated across a 430-Å region from the electric field of 90 Å of a depleted concentration of 2×10^{18} cm^{-3} charged acceptors. At low temperature $E_a = 0.4$ eV. In our view the most plausible mechanism which explains such behavior of the activation energy is the thermally assisted tunneling. This mechanism is illustrated in Fig. 3. At low temperatures the direct thermionic current over the barrier is small. The contribution of tunneling electrons at a given energy is proportional to the product of the number of electrons at this energy and the tunneling probability. The former exponentially decreases with energy according to the Boltzmann formula whereas the latter increases sharply with decreasing area of the barrier above the given energy. For a triangular barrier the quasi-classical tunneling probability[11] depends exponentially on energy to the power 3/2. The product of these two functions is sharply peaked at some energy E_a and the main contribution to the current is due to electrons with the energy near E_a. The quantity E_a in a given temperature range is the activation energy. Qualitatively, the temperature dependence of E_a shown in Fig. 3 is just what one would expect from the thermally assisted tunneling mechanism. Clearly this mechanism can be of importance only for very thin barriers and sufficiently low temperature. For example, this regime of thickness and temperature may become important in ballistic-transport TB devices, where low temperatures and small dimensions are necessary to meet ballistic condition requirements.

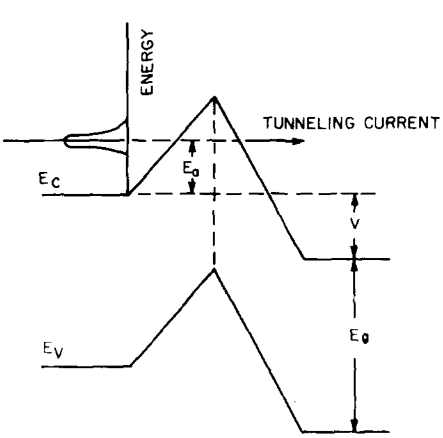

FIG. 3. Thermally assisted tunneling in thin TB diodes.

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