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Tunneling hot electron transistor as a high power source at terahertz frequencies

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A novel device is proposed, based upon a tunneling hot electron transfer amplifier, which exhibits the characteristics of negative differential resistance (NDR) coupled with high current gain. The mechanism which produces the NDR is known to be extremely fast. The combination of these features suggests that such a device could be used as a high power source of terahertz radiation. © *1994 American Institute of Physics.*

The exceptionally high speeds at which electrons tunnel or travel ballistically through ultrathin semiconductor layers makes devices based upon such transport capable of high frequency operation. Brown *et al.*[1] have demonstrated that an InAs/AlSb resonant tunneling diode can produce oscillations at frequencies up to 712 GHz. With careful design and fabrication such devices should be able to produce, mix and detect radiation well into the terahertz region of the electromagnetic spectrum.

The basic feature of such devices which makes them suitable for these applications is their highly nonlinear current–voltage relationships. Double barrier diodes are well known to exhibit regions of negative differential resistance (NDR) and also bistability in their current–voltage characteristics. When suitably biased these devices have more than one stable current state and can easily be made to oscillate between these states. However, the power output from these devices is presently very low at high frequencies [$\sim$0.2 μW at 420 GHz (Ref. 2)] making them virtually useless for any potential applications.

The device described here is based upon a tunneling hot electron transfer amplifier (THETA) which was originally proposed and demonstrated by Heiblum *et al.*[3] A schematic conduction band edge profile of such a device is shown in Fig. 1. The THETA is a unipolar device and consists of three n^+ GaAs regions (emitter, base, and collector) separated by $Al_xGa_{1-x}As$ tunnel barriers. The Al mole fraction x for the emitter and collector barriers is generally in the range 0.1–0.4 and the barrier widths are $\sim$10 and $\sim$100 nm, respectively. The base width is typically $\sim$50 nm to allow a good fraction of the injected electrons to reach the collector barrier without being scattered. In the common base mode operation of such a device the emitter-base bias V_{EB}, is used to tunnel inject electrons through the first $Al_xGa_{1-x}As$ (emitter) barrier into the base region. These electrons are injected at high energies and form a "hot" electron distribution. It has been shown[3] that $\sim$50% of this injected distribution traverses the base layer ballistically (i.e., without measurable scattering) to reach the collector contact by traveling over the second $Al_xGa_{1-x}As$ (collector) barrier. This second barrier acts as an energetic high pass filter for the incident electron distribution. This enables such a device to be used as a spectrometer to analyze the energy distribution of the injected electrons which reach the collector barrier and the scattering processes which occur in the thin base layer can be investigated.

In a recent investigation Brill *et al.*[4] used a THETA device in which the collector barrier was only 10 meV higher than the Fermi level in the base. It was found that for high enough injection energies eV_{EB}, the dc current transfer ratio ($\alpha = I_C/I_E$) exceeded unity. This implies that more electrons are collected than are injected and that an additional current is being generated in the base region.

The sequence of schematic conduction band edge profiles in Fig. 2 outlines the physical process which leads to the observed high current transfer ratio. The device is biased in the common emitter configuration (current amplifier mode) and the emitter–collector bias V_{CE} is fixed throughout, so that the base–collector junction is moderately forward biased with no injection current. This is important since large values of V_{BE} lead to a reversal of the field here and increase the barrier height for the excited electrons (hence reducing α). In Fig. 2(a) V_{BE} is zero, no electrons are injected, and hence there is no collected current. For $V_{BE}>0$ [Fig. 2(b)] a high energy distribution of electrons is injected into the base region. Some of these electrons reach the collector contact forming the collector current I_C, while those hot electrons which are strongly scattered in the base region form the base current I_B, which flows into the base contact. Some of the energy given up by the scattered injected electrons may be absorbed by electrons in the Fermi sea in the base region and these excited electrons form high energy tails to the electron distribution there [Fig. 2(c)]. Provided that the collector barrier is low enough these electrons can also be collected relatively easily and add to I_C. The collected excited electrons constitute a base current which flows in the opposite direction to the conventional one. As the injection energy is increased further [Fig. 2(d)], the energy given up by the relaxing electrons increases and hence a greater number of excited electrons are produced. For a suitably chosen collector barrier height a sufficient number of electrons can be excited from the Fermi sea to reduce the total base current to zero and eventually reverse its direction. This implies that the emitter–base junction can have a dc negative resistance in addition to an ac negative differential resistance.

A series of current–voltage relationships at various terminals of the device is shown in Fig. 3. Figure 3(a) is a plot of the dependence of the collector current on the injector bias showing an exponential increase which is related to the tun-

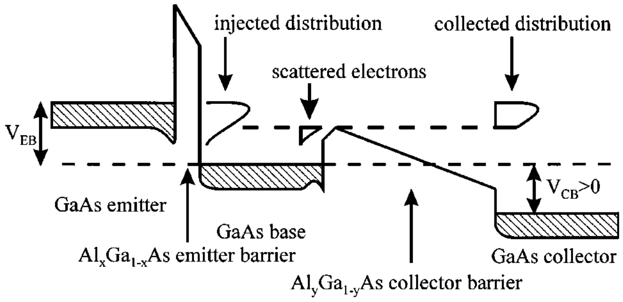

FIG. 1. Schematic conduction band edge profile of a tunneling hot electron transfer amplifier.

neling of electrons through the emitter barrier. Figure 3(b) shows the relationship between the collected and injected currents. Under normal conditions this curve would tend asymptotically towards the line $\alpha=1$. However, the contribution of the excited base electrons to the collector current means that $I_C>I_E$ and the curve tends to a line $\alpha>1$. At the point where $I_B=0$, $\alpha=1$ and the common emitter dc current gain $\beta=I_C/I_B=\alpha/(1-\alpha)=\infty$. Figure 3(c) shows the relationship between I_B and $V_{\rm BE}$ and the points labeled (a)–(d) in this figure relate to the various bias conditions shown in Fig. 2. The base current initially increases and then as an excited electron distribution is produced I_B starts to fall and eventually reverses in polarity. The slope of the curve beyond the point (b) gives the negative differential resistance of the emitter–base junction $1/R_{\rm BE}=-dI_B/dV_{\rm BE}$. This negative resistance can be made to oscillate in a suitably designed resonant circuit and this signal will be delivered with gain to a load at the collector terminal.

A schematic small signal equivalent circuit for the high frequency operation of this device is shown in Fig. 4. The device is operated in the common emitter configuration, where $g_m=dI_C/dV_{\rm BE}$ is the transconductance. The resistance and inductance $R_{\rm EXT}$ and $L_{\rm EXT}$ are extrinsic circuit components.

Assuming that parasitic impedances can be made as small as desired, the limiting factor which would determine the ultimate operating frequency of this device is the type of electron scattering event occurring in the base which leads to the production of the excited distribution. The two main mechanisms which need to be considered are electron–electron and electron–phonon scattering. The electron–electron mechanism is known to be very fast (~10–100 fs) whereas phonon related scattering events are relatively slow (~ps) and would restrict the frequency range of the device. Present results[5] indicate that the mechanism is electron–

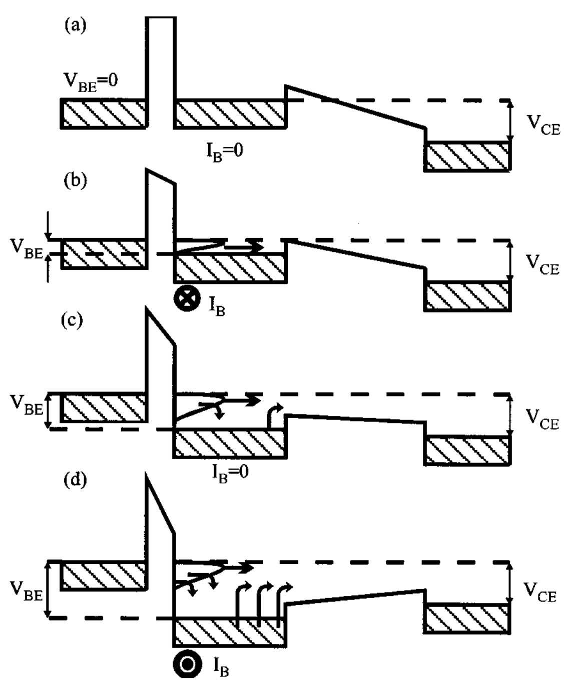

FIG. 2. Demonstration of the proposed negative resistance mechanism.

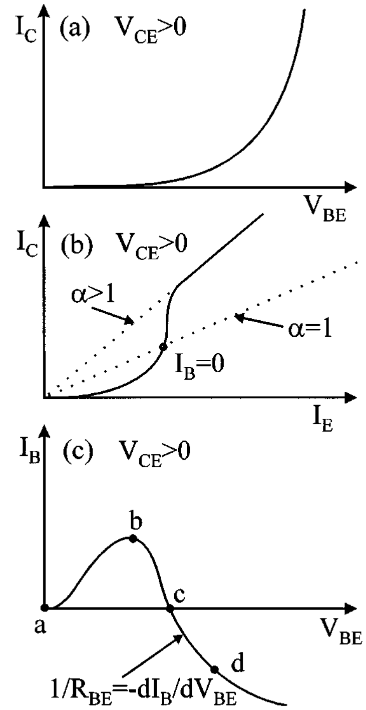

FIG. 3. Current–voltage relationships at various terminals in the device.

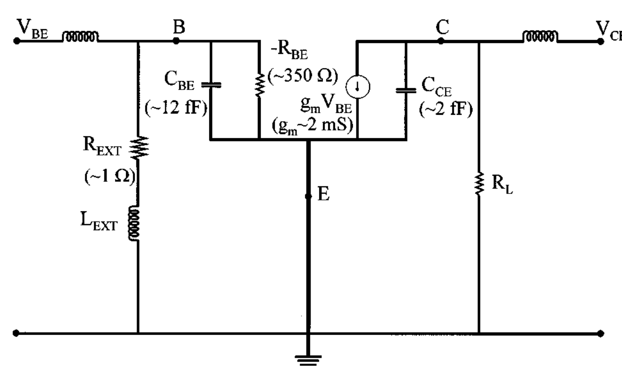

FIG. 4. High frequency equivalent small signal circuit for the proposed device.

electron related with an estimated relaxation time for injected electrons of ~250 fs. This would imply possible operating frequencies of up to 4 THz. However, the actual working frequency would be restricted by the various parasitic component values which arise due to the physical structure of the fabricated device. The negative resistance values scaled from the data of Brill *et al.*[5] for a 30 μm$\times$10μm indicate that a similar 1 μm$\times$1 μm device would oscillate up to 50 GHz with an output power of 1 nW. These low values are due to the low injected current density for this particular device. Halving the width of the emitter barrier in their structure from 19 to 9.5 nm would increase its transmission coefficient and hence the injected current density by a factor of 10^3. This would reduce correspondingly the negative resistance of the emitter–base junction increasing the maximum operating frequency to ~700 GHz with an output power of ~1 μW. These figures are based upon rough estimates of device parameters given in Fig. 4, which are scaled from the data of Ref. 5. A reduction in emitter barrier width would also lead to an undesirable increase in the width of the injected distribution which could be compensated for by lowering the emitter doping. The device of Ref. 5 suffered from small levels of leakage current arising from in-plane voltage drops in the base layer due to the large current densities flowing there. This could be overcome by biasing near $I_B=0$ and reducing the size of the device since the lateral voltage drop scales with the emitter contact area. Further optimization of the device structure would be expected to lead to improvements in these figures of several orders of magnitude. The low collector barrier height required for the collection of the excited electrons would, however, make low temperature $(T\leqslant 77\ \mathrm{K})$ operation of this device necessary in order to reduce the number thermally excited carriers in the base layer.

In conclusion a novel high frequency device has been proposed which is based upon ballistic transport in GaAs. This device would have a double advantage at high frequencies since it couples negative differential resistance with high current gain and is potentially capable of producing well in excess of 1 μW at 700 GHz.

We would like to thank B. Brill for making Refs. 4 and 5 available to us prior to publication.

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