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MBE-Grown GaAs Voltage-Controlled Bipolar-Unipolar Transition Negative Differential Resistance Power Transistor

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A GaAs voltage-controlled negative differential resistance power transistor using n^+-i-p^+-i-n^+ structure prepared by molecular beam epitaxy (MBE) are presented. The peak-to-valley current ratios (PVRs), peak current densities and generated power outputs can be easily modulated by changing the third external base to emitter bias. A highest PVR of 140 with V_{BE}=0.5V at room temperature has been obtained. This is proposed to be due to the bipolar-unipolar transition reaction. For power consideration, it can be compared with resonant tunneling hot electron transistors.

$1. INTRODUCTION

Recently, a GaAs voltage-controlled bipolar-unipolar transition negative differential resistance transistor (BUNDR) using n^+-i-p^+-i-n^+ structure has been demonstrated.[1,2] The PVRs can be adjustable by the applied base-emitter bias and can be expressed as $A\exp(BV_{BE})$, where A and B are geometry-dependent parameters.[3] The large PVR and calculated power output, e.g., PVR=300 and $P_{max} > 100W/cm^2$ at V_{BE}=5.5V, can be easily obtained at room temperature.[4] In this report, we demonstrate a power voltage-controlled BUNDR using a scaled down structure. Compared with the previous work,[1-4] the power output in this device has been greatly promoted. The present structure may possess several advantages: (1) adjustable PVRs (2) large PVRs even at room temperature (3) a higher power operation (4) ease of fabrication , and finally, (5) can be composed to logic circuits

$2. EXPERIMENT

The cross-sectional view of the MBE-grown power BUNDR is illustrated in Fig.1. Silicon and beryllium were used as n- and p-type dopants, respectively. The growth temperature was kept at 580°C with a growth rate of $1\mu mh^{-1}$.[5] A 0.4μm thick undoped GaAs layer was first grown on a Si-doped n^+-GaAs subatrate, followed by a thin p^+ layer, 110Å, with a high doping concentration of $5\times10^{18}cm^{-3}$. A 0.2μm thick undoped GaAs layer was then deposited. Finally, 0.2μm thick n^+ GaAs layer was grown as the emitter. V-groove technology[6] was used to contact the base layer. Au/Ge was used to form the ohmic contact of the n^+ layers while Au/Zn for the contact of p^+ base.

$3. RESULTS AND DISCUSSION

The typical I/V characteristics for this power BUNDR at various base-emitter voltages are illustrated in Fig.2. NDR phenomena are observed clearly at $V_{BE} > 0$. This is resulted from the transition from the bipolar mode to the unipolar mode.$^{1-4)}$ The I/V characteristics for $V_{BE} > 0$ can be segmented into three regions and discussed as follows:

(a) Bipolar region for $0 < V_{CE} < V_P$ (peak current voltage)

(b) NDR region for $V_P < V_{CE} < V_V$ (Bipolar-unipolar transition region)

(c) Unipolar region for $V_{CE} > V_V$ (valley current voltage)

Figure 1 sketches the model for the current components and relative parameters. The corresponding neutral base length (L-L'), base current and collector current are as a function of V_{CE}.

(a) Bipolar region for $0 < V_{CE} < V_P$

In this region, there is neutral region in base and can be considered as a conventional bipolar transistor with the collector current increasing with increasing V_{BE} bias. According to the characteristics shown in Fig.1. V_{CI} increases with increasing V_{BE} bias. The interpretation is due to the leak current of base. For small V_{BE} bias, base current I_B is small. As V_{BE} increases, I_B also increases. At a low constant V_{CE} for large V_{BE}, I_B increases due to electrons drawn by the forward biased base. The diffused electrons over the base barrier injected to collector are reduced. This requires larger V_{CE} to supply electrons for the same collector current, i.e., V_{CI} increases with increasing V_{BE} bias.

As $V_{CE} > V_{CI}$, the forward bias between base and emitter enhances the electrons injected to the collector, thus, I_C increases with increasing V_{CE} as a conventional transistor. As $V_{CE} = V_P$, the collector current reaches a maximum. At this moment, the base width begins to be depleted, i.e., a punch through mode is established. This initialized region is indicated as B'.(Fig.1) As V_{CE} is further increased above V_P, the effective base channel length (L-L') is decreased while the depletion base length (B'-B'=L') is increased. The current is dominated by diffusion current (J_{diff}) due to bipolar transistor. For a fixed V_{CE}, I_C increases with increasing V_{BE} as a conventional transistor. I_B is maximum at $V_{CE}=0$ for a fixed V_{BE}. I_B decreases with increasing V_{CE} due to the reduction of recombination in base.

(b) NDR region for $V_P < V_{CE} < V_V$ (Bipolar-unipolar transition region)

The increasing of V_{CE} rises the base potential at the point B' shown in Fig.1.

Since the p^+-region is narrow, the spreading resistance is high. The voltage across $R_{BB'}$ is large. Emitter current crowding effect may be serious. The applied V_{CE} is also divided by resistance of the undoped i-layers, which also plays an important role for the device performance. As the neutral base width at B' for a constant V_{BE} is zero due to the increase of V_{CE}, no longer a forward bias exists between B'and E, i.e., a punch-through mode is established at point B'. $V_{B'E}$ may be driven into reverse bias as compared to V_{BE}. The available neutral base length (L-L') for electrons injected to the collector is decreased resulting in a decreasing of I_C, i.e., NDR characteristics occur. The observed results can be confirmed by the facts that V_P increases with increasing V_{BE}. The larger V_{BE} , the point B' to reach the zero base channel width requires a larger V_{CE}.

As $V_{CE} > V_P$, B' moves toward B with increasing V_{CE} as illustrated by the arrow shown in Fig.1. The corresponding neutral base (L-L') decreases while depleted base length L' increases. Hence, I_C decreases with increasing V_{CE} . As B' is close to B, i.e., L-L'=0, thus, the base region is fully depleted and can be considered as a planar-doped-barrier devices. The current component is then dominated by thermionic current (J_{th}) while not diffusion current. The total current is then the combination of diffusion current and thermionic emission current. The reduction of I_{diff} is larger than the increase of I_{th}. Thus, I_C decreases with increasing V_{CE}.

(c) Unipolar region for $V_V < V_{CE}$

In this case, the base is fully depleted at $V_{CE}=V_V$ and can be considered as a planar doped barrier unipolar device. Electrons have more energies to overcome the barrier and thermionically emitted over it, then I_C increases again with increasing V_{CE}. The current is dominated by thermionic emission current. $J=J_{th}+J_{diff} \simeq J_{th}$. A N-shape NDR characteristics is thus formed.

The observed NDR phenomenon is attributed to the decrease of the neutral base region. The current components include diffusion current and thermionic current, i.e., the NDR transition occurs due to a combination of bipolar and unipolar devices. In brief, considering the operation of the proposed model, the novel transistor is a bipolar-unipolar NDR (BUNDR) transistor.

As $V_{BE} < 0$, the base region is fully depleted in the beginning due to the reverse bias at the base and emitter junction. In this case, this device acts as a unipolar transistor(6). It can be regarded as a triangular barrier transistor. When the V_{BE} voltage is more negative, the I/V curve is shifted to the right due to the increase of the internal barrier height.(6) There is a little negative region revealed while V_{BE}=-

1V and -1.5V. This can be considered as a npn diac observed in separated experiments.$^{7)}$ The PVRs as a function of V_{BE} are shown in Fig.2. The maximum value of 140 at V_{BE}=0.5V has been obtained at room temperature. The improvement on the current output and the high PVR have made it possible as a candidate of power transistor.

§4. SUMMARY

In conclusion, a GaAs bipolar-unipolar transition NDR power transistor has demonstrated the interesting multiple N-shaped I/V characteristics. The PVRs can be easily modulated by changing the applied positive base-emitter bias. When applying a negative base-emitter bias on this device, it operates like a bulk barrier transistor as expected.

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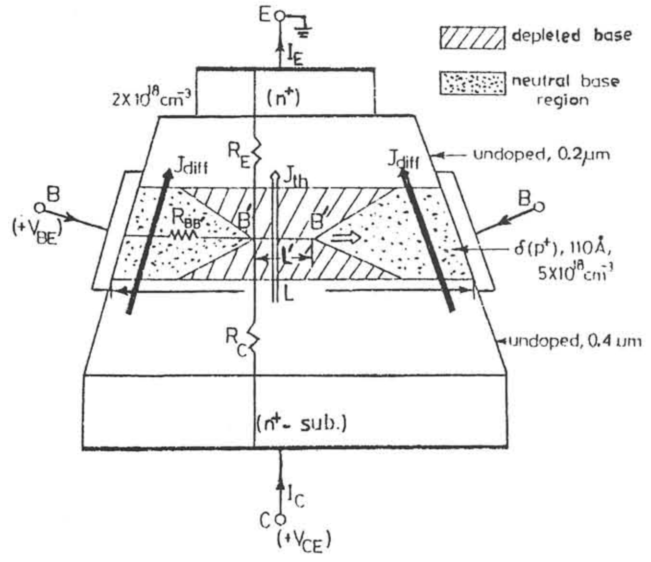

Fig. 1. The cross-sectional view of the MBE-grown power NDR transistor.

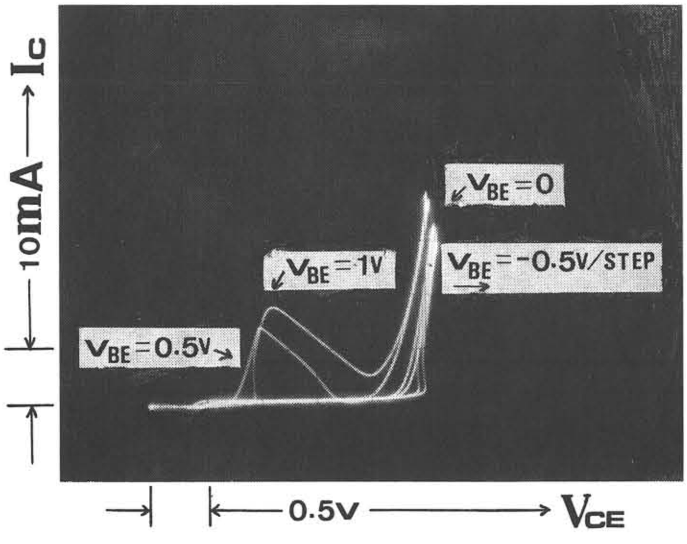

Fig. 2. The typical I/V characteristics of the power NDR transistor.