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Detailed experiments were carried out to establish the working epitaxial layer structure for the InAs high velocity transistors (InAs HVT). Appropriate InAlAsSb barrier and high purity InAs were incorporated into the final InAs HVT transistor structure. Molecular beam epitaxial (MBE) growth parameters were optimized for the InAs HVT. InAs HVT has been achieved, showing the first such vertical structure with world record transconductance and high speed device parameters. The input, output, and transfer characteristics of an InAs HVT in the common-base configuration were characterized. All the device characteristics were much improved than any previous established results, thus confirming the advantages of the innovative InAs HVT device design.

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InAs HVT for extremely low power and high speed applications

Annual Performance Report

Contract period: Sept. 30, 2003 - Sept. 29, 2004

Air Force Office of Scientific Research
Contract Number: F49620-01-1-0538

Principal Investigator:

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Summary:

Detailed experiments were carried out to establish the working epitaxial layer structure for the InAs high velocity transistors (InAs HVT). Appropriate InAlAsSb barrier and high purity InAs were incorporated into the final InAs HVT transistor structure. Molecular beam epitaxial (MBE) growth parameters were optimized for the InAs HVT. InAs HVT has been achieved, showing the first such vertical structure with world record transconductance and high speed device parameters. The input, output, and transfer characteristics of an InAs HVT in the common-base configuration were characterized. All the device characteristics were much improved than any previous established results, thus confirming the advantages of the innovative InAs HVT device design.

1. Program Goals

The goals of the program are to achieve extremely high speed (TeraHz) and low power (femto joules) operation of InAs High Velocity Transistor (HVT) by bringing out the best material properties of InAs, including high electron velocity for short transit time and high electron mobility for low base resistance of the transistor.

2. Description of technical work and achievements

During the third year period, i.e., the final year of this program, extensive material efforts by molecular beam epitaxy (MBE) were carried out to achieve suitable device quality MBE layer structures.

The critical barrier material, i.e., InAlAsSb was studied in detail through extensive in-situ reflection high energy electron diffraction and ex-situ X-ray diffraction measurements. Under optimized substrate temperature (460 C), appropriate digital alloy growth produced suitable quality materials for the InAs HVT.

With optimized device design and state-of-the-art quality materials, InAs HVT has been achieved under this program, with device transconductance high than any previous achieved InAs HEMT and HBT-based results. The InAs HVT device parameters achieved under this program are superior than any previous published results for high frequency operation.

The ideal InAs HVT device model are shown in the Fig. 1 (the energy band diagram), Fig. 2 (the equivalent circuit), Fig. 3 (energy band diagram showing partial blocking and partial transmission of the ballistic electrons), and Fig. 4 (output characteristics for the common-base configuration of the InAs HVT).

InAs HVT

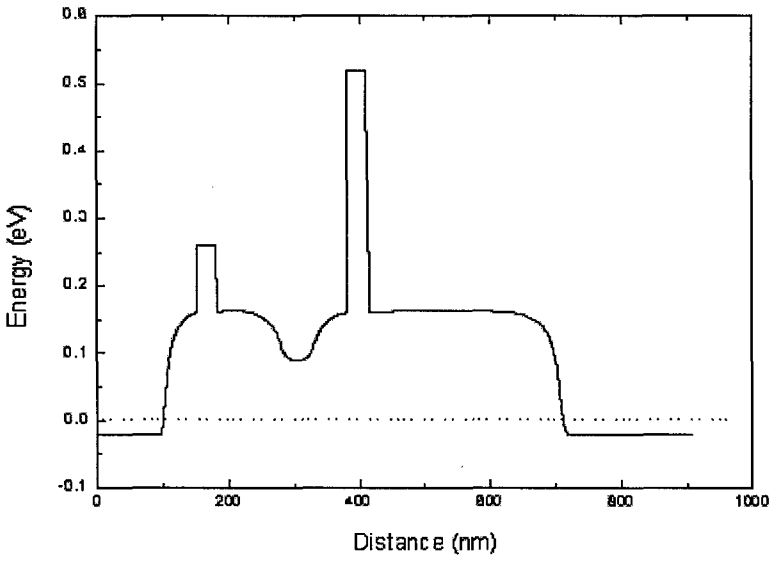


Fig. 1 Energy band diagram of the InAs HVT

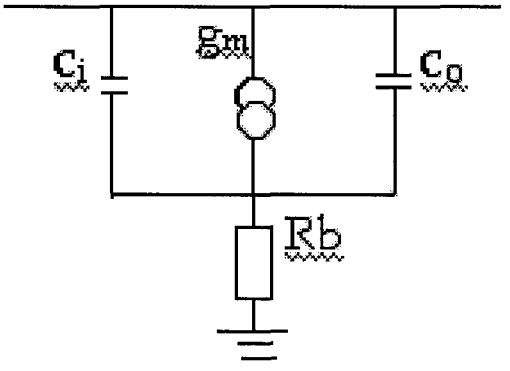


Fig. 2 The equivalent circuit of the InAs HVT as an analog device.

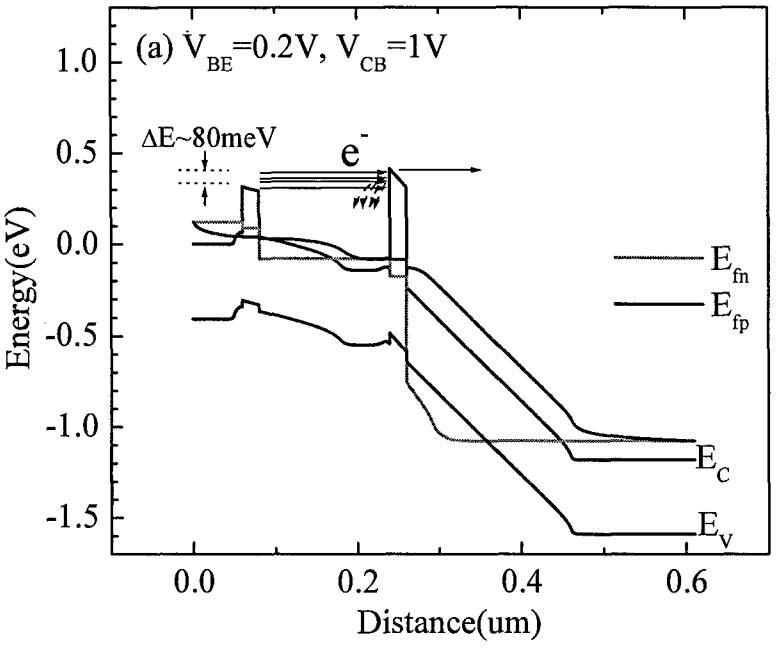


Fig. 3 Energy band diagram showing the InAs HVT operation.

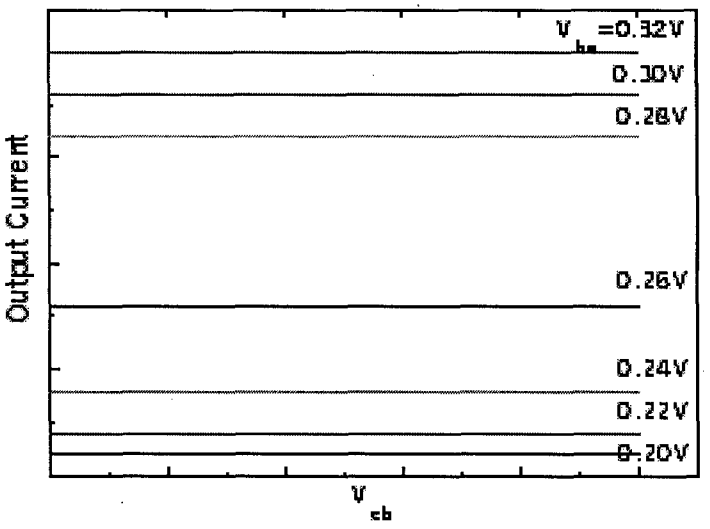


Fig. 4 Common-base output characteristics

Device performance of the InAs HVT

In Fig. 4 shown above, the output characteristics of an InAs HVT in the common-base configuration clearly shows the device advantage of the novel vertical transistor. As can be seen, the input differential resistance is very high because the bias current is determined by the emitter heterojunction barrier height. The actual value of low-frequency short-circuit current gain is determined by the resistance shunting C_i. The current in this shunt represents thermalized electrons in the base region. The actual value of low-frequency open-circuit voltage gain depends on the resistance shunting C_o. The current in this shunt represents direct electron emission over the collector-base barrier. At high frequency, the power gain of the HVT is very high because the input impedance is very high and the transconductance is also very high. Since the InAs HVT can be operated at very low current and power dissipation, its noise figure can be much better than that of any existing HEMT or HBT-based devices at extremely high frequencies.

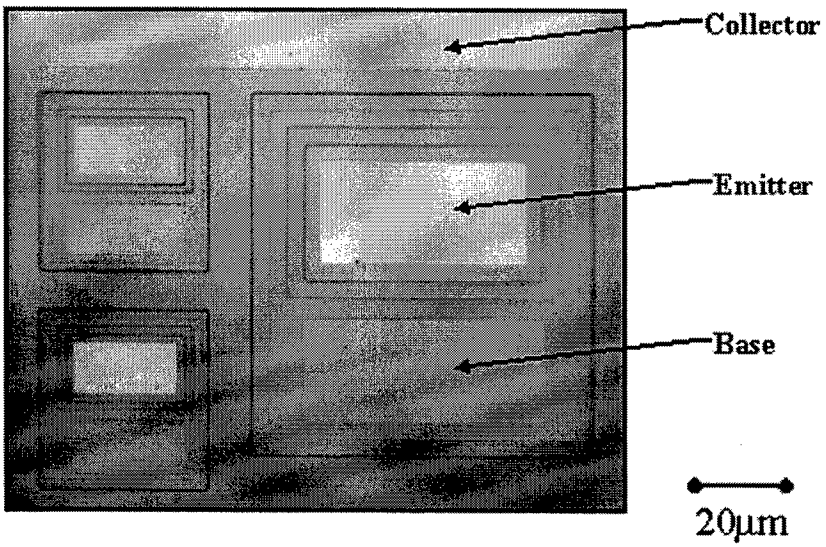


Fig. 5 The mask designed for the InAs HVT

The InAs HVT was grown by MBE and fabricated into a structure with four-level mesas. As shown in Fig. 5, two of which are passivation ledges. Standard photolithography and selective wet chemical etching techniques were employed. After the selective etching, the sample was immediately immersed into a freshly prepared, room-temperature P_2S_5:$(NH_4)_2S_x$:H2O passivation solution. The emitter, base, and collector were all contacted from the top using non-alloyed Ti/AuGe.

The transfer characteristics of the InAs HVT are shown in Fig. 6 and Fig. 7. The expected current-voltage characteristics have been achieved. The measured transconductance for a device with 7×14 μm^2 emitter size is as high as 1880 mS/mm at 80 K and 780 mS/mm at 300 K. These are the best device parameters reported so far either for HEMT or HBT-based device structures, thus confirming that the innovative device design of the InAs HVT has brought out the best device parameters of the InAs, i.e., high electron mobility and high electron velocity.

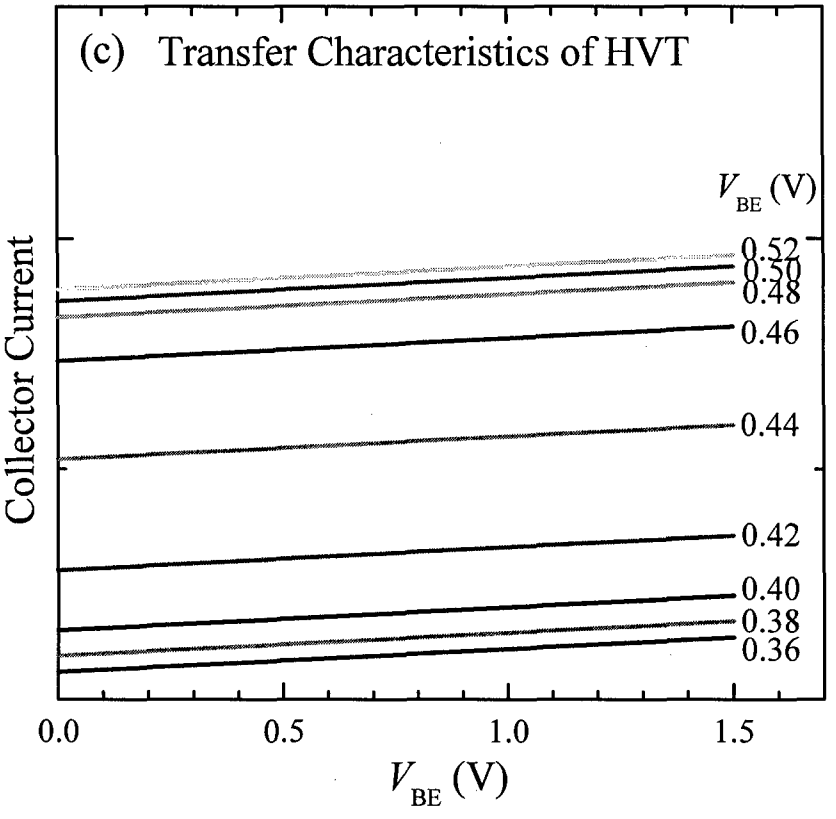


Fig. 6 The transfer characteristics of the InAs HVT at 300K

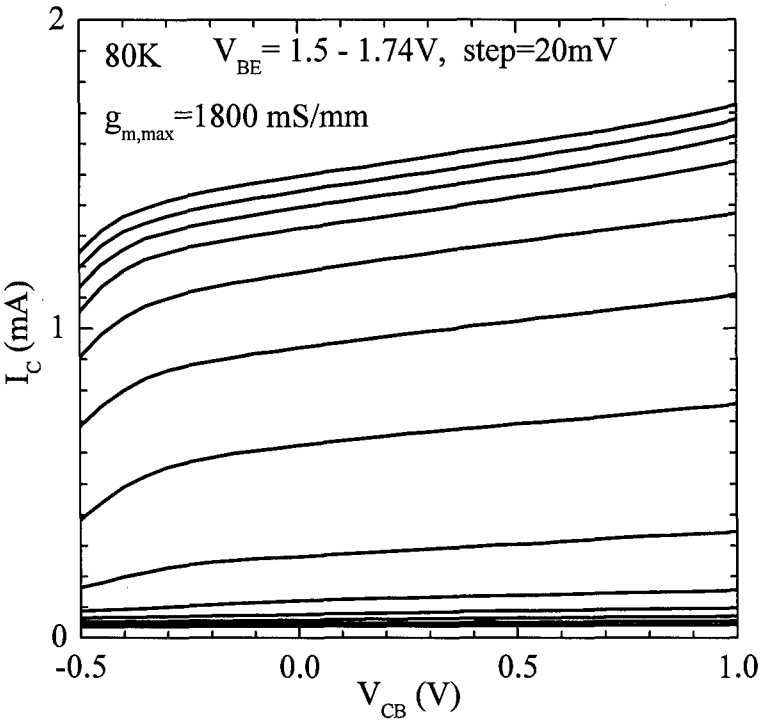


Fig. 7 The transfer characteristics of the InAs HVT at 80K

For analog circuit applications, the maximum frequency of oscillation may be estimated as

$$f_{\max} = \frac{1}{2\pi}\sqrt{\frac{g_m}{C_i C_o R_b}} \tag{1}$$

assuming a matched load impedance and a simple-pole roll-off of the current transfer ratio. In (1), R_b is the base resistance, which is reduced due to the high mobility in InAs and can be 2.5 ohms. With an operating current of 2.5 mA, the transconductance is 0.1 S and f_{max} = 3 THz.

For comparison, the performance of the best 0.1-um gate length InGaAs HEMT is

discussed here, using the same equivalent circuit and neglecting all parasitic parameters. The scaled-down 30-μm gate small-signal low-noise device works at V_{DS} = 2 V and I_{DS} = 9 mA, with g_m = 26.4 mS, R_S = 5.6 Ω, C_i = 36 fF and C_o = 5 fF. The calculated f_{max} = 800 GHz, which is consistent with the measured value of 600 GHz. As can be seen, the value of f_{max} for the InAs HVT is 3 times higher than that of the 0.1-um gate-length HEMT.

3. Personnel supported:

Associated Research Scientist: Dr. S. Xin

Graduate Research Assistants: Y.C. Chen, Weiping Li, and Sheyum Syed

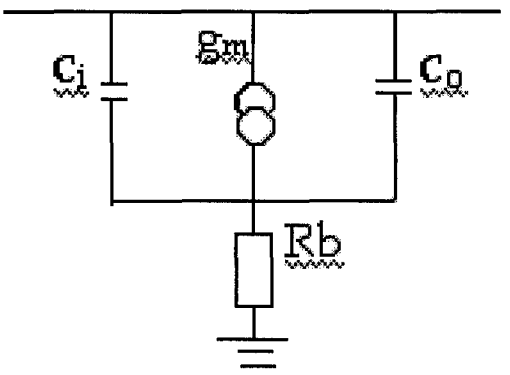


Fig. 13 The equivalent circuit of the InAs HVT as an analog device.

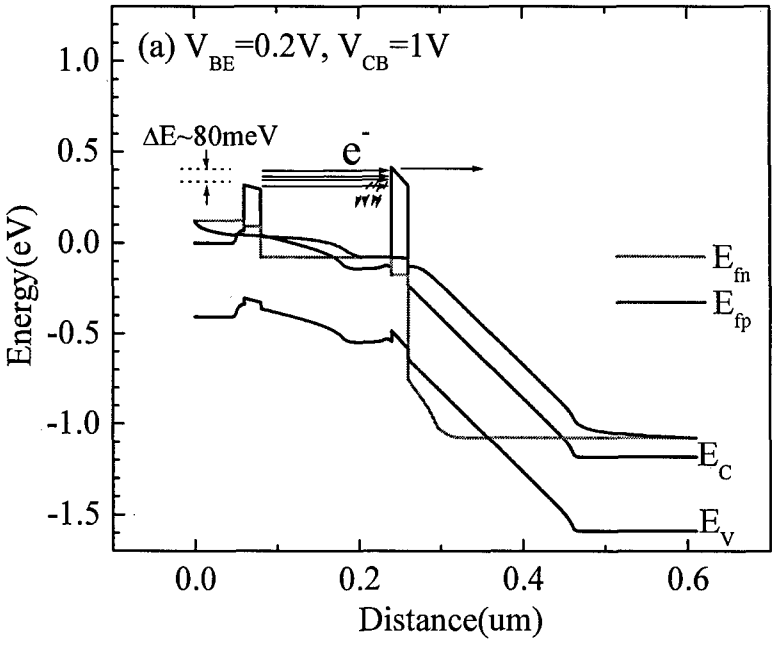
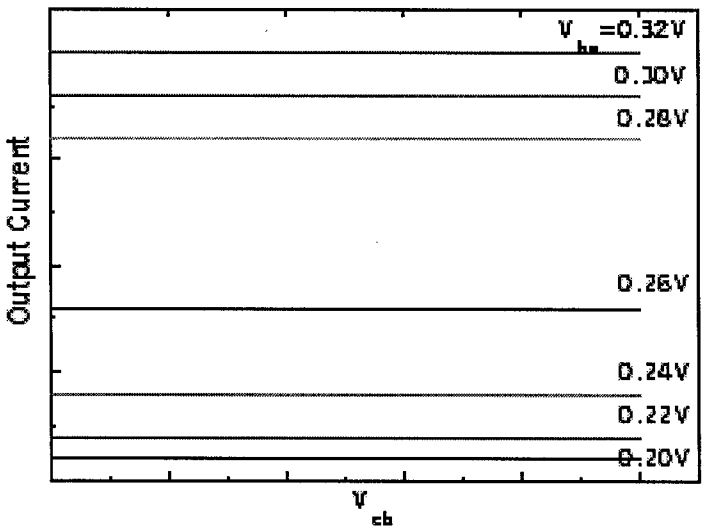


Fig. 14 Energy band diagram showing the InAs HVT operation.



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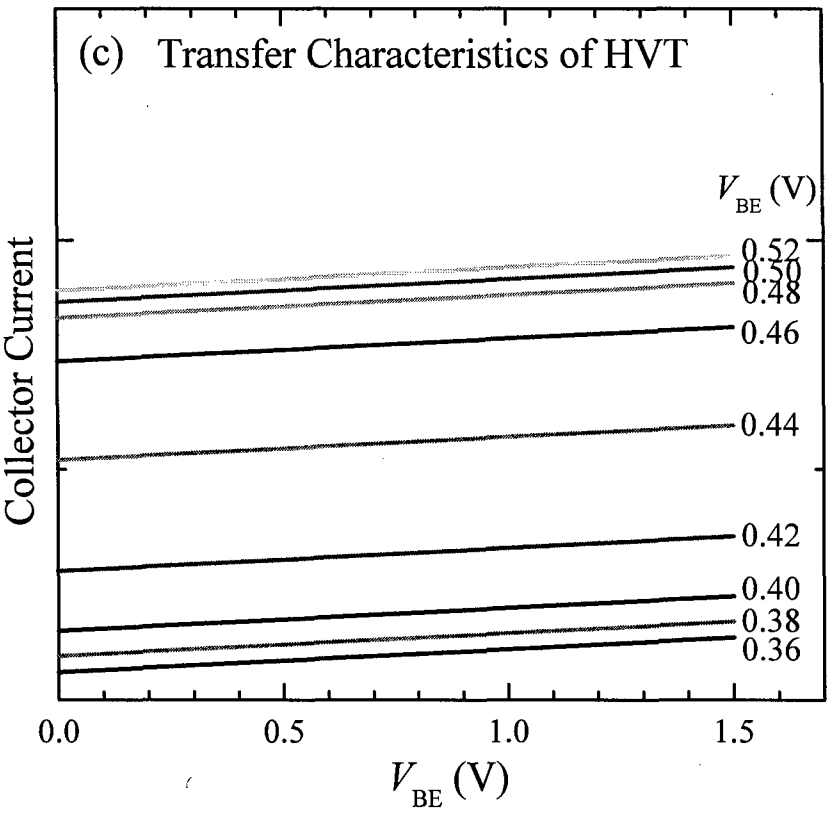

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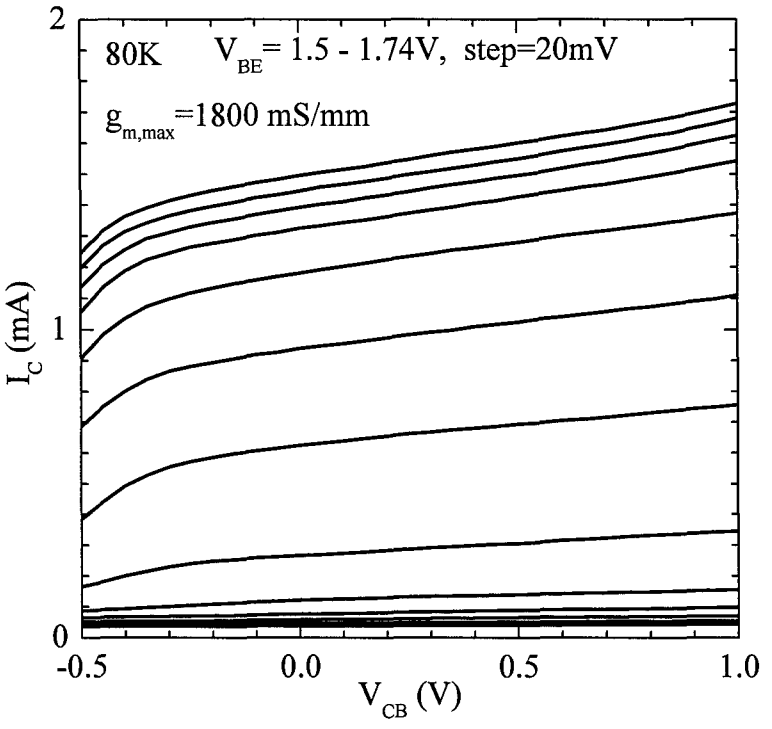

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