Microwave Frequency Operation of the Heterostructure Hot-Electron Diode

J. KOLODZEY, J. LASKAR, T. K. HIGMAN, M. A. EMANUEL, JAMES J. COLEMAN, SENIOR MEMBER, IEEE, AND KARL HESS, FELLOW, IEEE

Abstract—**We report the first generation of microwave frequencies by the heterostructure hot-electron diode (H^2ED). At 77 K, self-oscillations have been produced over a broad frequency range from direct current to 10.5 GHz, limited by the parasitic series resistance and capacitance. Considerations of the bias polarity required to produce oscillations and of their high-frequency response support a model of switching from tunneling to thermionic emission.**

I. INTRODUCTION

TWO-TERMINAL compound semiconductor devices are under intense investigation for sources of ultrahigh-frequency signals. Resonant tunneling devices [1] can oscillate at frequencies of 200 GHz [2]. Transit-time microwave devices such as the IMPATT can produce high output powers, but over narrow bands with the center frequency determined by the drift velocity and the device length. The relatively high noise figure of IMPATT's is another limitation [3]. The high electron mobility transistor (HEMT) has produced amplification at 94 GHz, which is somewhat lower than the frequency response of two-terminal devices [4].

In this letter we describe the first high-frequency measurements of the heterostructure hot-electron diode (H^2ED), a negative differential resistance (NDR) device which according to theoretical predictions may have an ultimate response time as short as 200 fs [5]. Fig. 1(a) shows the band diagram for conditions of low forward bias. The left contact is made negative and the electric field in the left-most low-gap region is zero due to charge accumulation at the left interface. For this case of no electric field in the left low-gap region, current flows by the tunneling of electrons through the barriers. At high forward bias, electrons become heated and are excited over the barriers by thermionic emission. The band diagram for this case of high electric fields is shown in Fig. 1(b), indicating a redistribution of fields with increased electric field in the low gap region at the left (see [6] for a complete explanation of the switching). The two conduction mechanisms of tunneling and thermionic emission cause two branches in the current–voltage (I–V) characteristic, as shown in Fig. 2. At a characteristic voltage, the conduction switches from tunneling to thermionic emission resulting in S-shaped NDR for positive bias. Under negative bias, no NDR occurs.

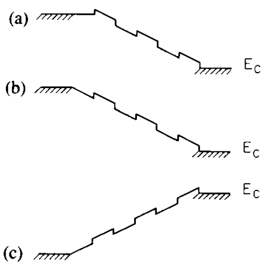

Fig. 1. Band diagram of the H^2ED showing: (a) low forward-bias tunneling mode with negligible electric field in left-most low-gap layer; (b) high forward-bias thermionic emission mode with significant electric field in left low-gap layer; and (c) reverse-bias mode with impact ionization but no switching.

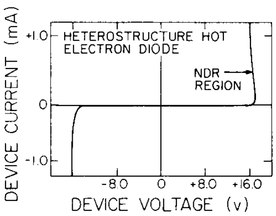

Fig. 2. Typical current versus voltage characteristic of the H^2ED showing switching at + 16 V and 0.5 mA, at 77 K. In the low-current branch below 0.2 mA, tunneling dominates. In the high-current branch greater than 0.8 mA, thermionic emission dominates.

The H^2ED structure is distinct from other heterostructure devices which may operate by an electron heating mechanism. For example, there are certain similarities to a selectively doped NDR device reported by Belyantsev *et al.* [7] which has produced oscillations at 10 GHz. This device, however, is reported to require a heavily doped low-gap well [8], unlike the H^2ED which has demonstrated NDR in a structure with undoped wells [5]. For the high-frequency measurements reported in this letter, the particular H^2ED device structure consists of three barriers and three wells as described in the next section.

II. DEVICE FABRICATION AND CHARACTERISTICS

The device multilayers were grown by metalorganic chemical vapor deposition (MOCVD) on n^+ GaAs substrates as described elsewhere [6]. A schematic cross section of the

---

Manuscript received February 5, 1988. This work was supported in part by the National Science Foundation Engineering Research Center for Compound Semiconductor Microelectronics, and the Joint Services Electronics Program.

The authors are with the Center for Compound Semiconductor Microelectronics, University of Illinois at Urbana-Champaign, Urbana, IL 61801.

IEEE Log Number 8821310.

0741-3106/88/0600-0272$01.00 © 1988 IEEE

device is shown in Fig. 3. The device reported here has three periods of $Al_{0.45}Ga_{0.55}As$ barriers alternating with GaAs wells. An n^+ GaAs cap layer and an n^+ substrate provide low series resistance. To process wafers into devices, ohmic contacts are formed using alloyed AuGe/Ag/Au layers which are patterned into 50-μm-diameter dots by a lift-off process. Mesas containing the active layers are defined using wet chemical etching. The *I*–*V* characteristic of the fabricated device is shown in Fig. 2 for a measurement temperature of 77 K.

III. HIGH-FREQUENCY OPERATION

For high-frequency measurements, a wafer section containing several device mesas was mounted in a coaxial test fixture having an SMA connector. Contact to a particular mesa is made with a fine tungsten wire. The test fixture is immersible in liquid nitrogen and all measurements reported here were made at 77 K. The test fixture was connected to a coaxial cable having a 50-Ω characteristic impedance and a frequency response to 18 GHz. For measurements of amplitude and frequency, the device and cable assembly were attached to a spectrum analyzer (Hewlett-Packard 8566A). To reduce noise, the resolution and video bandwidths of the spectrum analyzer were set to 3 kHz.

Device bias was applied through a T-network having frequency response to 26 GHz. For precision voltage adjustment, a five-digit power supply was used (Hewlett-Packard 6115A). Free-running self-oscillations were produced when the device bias was adjusted to ~ +16 V. The exact voltage was adjusted during the measurements to compensate for device heating effects. The H^2ED produced oscillation spectral lines from dc to 10.5 GHz.

To further concentrate the output power into bands of frequency, the device fixture was connected to a resonator consisting of a coaxial line stub located 4 cm from the H^2ED. Output power versus frequency for the resonator circuit is shown in Fig. 4. Due to losses in the resonator and cables, the oscillation frequency is not highly selective and the harmonics are not precisely spaced. Spectral lines appear at intervals of approximately 1 GHz. The maximum frequency line is at 10.5 GHz with a power of −84 dBm. The instrumentation noise floor was less than −95 dBm, so the measurement signal-to-noise ratio was ~10 dB. At 300 K, oscillations were not observed, perhaps due to the competition of thermal currents at room temperature with the basic switching mechanism.

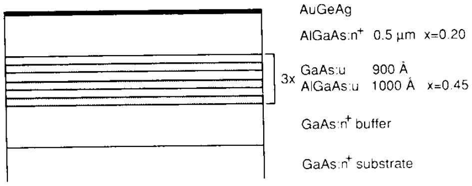

Fig. 3. Schematic cross section of H^2ED structure showing metal contact to top of mesa and semiconductor layer thicknesses and Al mole fraction x. n^+ indicates Si doping at $2 \times 10^{18} cm^{-3}$ and u indicates undoped. For negative differential resistance, electron flow is from top of mesa to bottom.

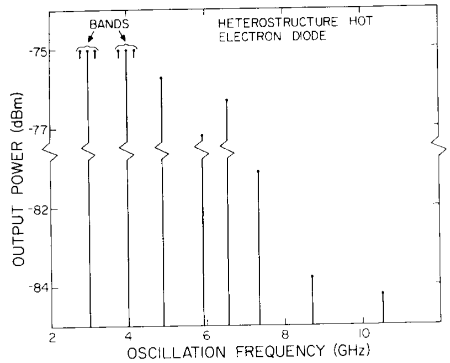

Fig. 4. Oscillation power versus frequency of the H^2ED in a resonator circuit. Harmonics measured with spectrum analyzer show spectral lines up to 10.5 GHz.

The theoretical maximum frequency of oscillation $f_{\max,0}$ for the H^2ED is limited by the transit time τ across the device active region:

$$f_{\max,0} = \frac{1}{2\pi\tau}. \tag{1}$$

For the device reported here, the active region length is 3 × 190 nm = 570 nm. Assuming an average electron drift velocity of 1×10^7 cm·s^{-1}, the transit time τ = 5.7 ps, corresponding to a maximum frequency of 28 GHz. This value of $f_{\max,0}$ exceeds the measured maximum frequency. The reason is that parasitic elements such as device capacitance C and series resistance R_s limit the maximum frequency in a practical circuit. The maximum frequency limited by parasitics is given by [3]

$$f_{\max} = \frac{1}{2\pi R_n C}\left(\frac{R_n}{R_s} - 1\right)^{1/2}. \tag{2}$$

For our device, C = 0.3 pF, R_s = 2 Ω, and negative resistance magnitude R_n = 1000 Ω. With these values, we calculate $f_{\max}$ = 11.9 GHz, which is closer to our measured value of 10.5 GHz.

To verify that the oscillations were not caused by other mechanisms such as impact ionization, we operated the device in reverse bias, making the left contact positive as in Fig. 1(c). The reverse dc *I*–*V* characteristic was smooth with no evidence of NDR. The presence of impact ionization was indicated by the emission of infrared light due to the recombination of electrons with holes, but no oscillations were observed over a range of reverse bias conditions. Under forward bias conditions, the high frequency of the oscillations precludes a mechanism associated with the ionization of deep impurities which has a maximum frequency response well under 1 GHz [9], [10]. Both of the above considerations support our conclusion that oscillations are caused by the mechanism of switching from tunneling to thermionic emission proposed in [5].

IV. CONCLUSION

Our measurements demonstrate that the H^2ED is a source of wide-band microwave power at 77 K. By operating the H^2ED in the negative differential resistance mode in a resonant circuit, self-oscillations were produced in a 50-Ω system over a broad frequency range from dc to 10.5 GHz. The maximum frequency of oscillation was limited by parasitic elements. These experiments support an operating mechanism of switching between tunneling and thermionic emission.

ACKNOWLEDGMENT

The authors would like to thank N. Holonyak, Jr., P. Klock, and G.E. Stillman for useful advice.

REFERENCES

[1] F. Capasso, K. Mohammed, and A. Y. Cho, "Resonant tunneling through double barriers, perpendicular transport phenomena in superlattices and their device applications," *IEEE J. Quantum Electron,* vol. QE-22, pp. 1853-1869, 1986.

[2] E. R. Brown, T. C. L. G. Sollner, W. D. Goodhue, and C. D. Parker, "Fundamental oscillations up to 200 GHz in a resonant-tunneling diode," *IEEE Trans. Electron Devices,* vol. ED-34, p. 2381, 1987.

[3] S. M. Sze, *Physics of Semiconductor Devices,* 2nd ed. New York: Wiley, 1981, p. 534.

[4] P. M. Smith, P. C. Chao, K. H. G. Duh, L. F. Lester, and B. R. Lee "94 GHz transistor amplification using an HEMT," *Electron. Lett.,* vol. 22, pp. 780-781, 1986.

[5] K. Hess, T. K. Higman, M. A. Emanuel, and J. J. Coleman, "New ultrafast switching mechanism in semiconductor heterostructures," *J. Appl. Phys.,* vol. 60, pp. 3775-3776, 1986.

[6] T. K. Higman, J. M. Higman, M. A. Emanuel, K. Hess, and J. J. Coleman, "Theoretical and experimental analysis of the switching mechanism in heterostructure hot electron diodes," *J. Appl. Phys.,* vol. 62, pp. 1495-1499, 1987.

[7] A. M. Belyantsev, A. A. Ignatov, V. I. Piskarev, M. A. Sinitsyn, V. I. Shashkin, B. S. Yavich, and M. L. Yakovlev, "New nonlinear high-frequency effects and S-shaped negative differential conductivity in multilayer heterostructures," *JETP Lett.*, vol. 43, pp. 437-441, 1986.

[8] Zh. I. Alferov, O. A. Mezrin, M. A. Sinitsyn, S. I. Troshkov, and B. S. Yavich, "Mechanism of an S-shaped current-voltage characteristic in a multilayer isotypic GaAs-AlGaAs heterostructure," *Sov. Phy.—Semicond.,* vol. 21, pp. 304-307, 1987.

[9] N. Holonyak, Jr., private communication, 1987.

[10] A. G. Milnes, *Deep Impurities in Semiconductors.* New York: Wiley-Interscience, 1973, p. 333.