Microwave Frequency Operation of the Heterostructure Hot-Electron Diode


Abstract—We report the first generation of microwave frequencies by the heterostructure hot-electron diode (H'ED). 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'ED), 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.

The H'ED 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'ED which has demonstrated NDR in a structure with undoped wells [5]. For the high-frequency measurements reported in this letter, the particular H'ED 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
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 contain-
ing 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 adjust-
ment, 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'ED 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'ED. 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.

The theoretical maximum frequency of oscillation \( f_{max} \) for
the H'ED is limited by the transit time \( \tau \) across the device
active region:
\[
    f_{max} = \frac{1}{2\pi} \frac{1}{R_s C} \left( \frac{R_s}{R_t} - 1 \right)^{1/2}.
\]

For the device reported here, the active region length is 3 ×
190 nm = 570 nm. Assuming an average electron drift
velocity of \( 1 \times 10^7 \text{ cm·s}^{-1} \), the transit time \( \tau \approx 5.7 \text{ ps} \),
corresponding to a maximum frequency of 28 GHz. This value
of \( f_{max} \) exceeds the measured maximum frequency.
The reason is that parasitic elements such as device capacitance \( C \)
and series resistance \( R_t \) limit the maximum frequency in a
practical circuit. The maximum frequency limited by parasitics is given by [3]
\[
    f_{max} = \frac{1}{2\pi R_s C} \left( \frac{R_s}{R_t} - 1 \right)^{1/2}.
\]

For our device, \( C = 0.3 \text{ pF} \), \( R_t = 2 \Omega \), and negative resistance magnitude \( R_s = 1000 \Omega \). With these values, we
calculate \( f_{max} = 11.9 \text{ GHz} \), 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 emis-

IV. CONCLUSION

Our measurements demonstrate that the H'ED is a source of
wide-band microwave power at 77 K. By operating the H'ED
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.

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References

through double barriers, perpendicular transport phenomena in su-
perlattices and their device applications,” IEEE J. Quantum Elec-
“Fundamental oscillations up to 200 GHz in a resonant-tunneling
ultrafast switching mechanism in semiconductor heterostructures,” J.
Coleman, “Theoretical and experimental analysis of the switching
mechanism in heterostructure hot electron diodes,” J. Appl. Phys.,
Shashkin, B. S. Yavich, and M. L. Yakovlev, “New nonlinear high-
frequency effects and S-shaped negative differential conductivity in
S. Yavich, “Mechanism of an S-shaped current-voltage characteristic
in a multilayer isotopic GaAs-AlGaAs heterostructure,” Sov. Phys.—