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Self-sustained current oscillation above 100 GHz in a GaAs/AlAs superlattice

E. Schomburg,^{a)} M. Henini, and J. M. Chamberlain

School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, United Kingdom

D. P. Steenson

School of Electronic and Electrical Engineering, The University of Leeds, Leeds LS2 9JT, United Kingdom

S. Brandl, K. Hofbeck, and K. F. Renk

Institut für Angewandte und Experimentelle Physik, Universität Regensburg, Universitätsstr.31, 93040 Regensburg, Germany

W. Wegscheider

Walter-Schottky-Institut, Technische Universität München, Am Coulombwall, 85748 Garching, Germany

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A GaAs/AlAs superlattice with a large miniband (120 meV) showed self-sustained current oscillation at a frequency of 103 GHz giving rise to microwave emission (power 0.5 mW). The emission line had a linewidth of about 1 MHz and was tuneable by about 800 MHz. An analysis suggests that the transport in the superlattice was mainly due to electrons in the lowest miniband and that the oscillation was caused by traveling dipole domains. We also observed frequency locking of the current oscillation attributed to a synchronization of domain propagation by the external high-frequency field. © 1999 American Institute of Physics. [S0003-6951(99)02215-9]

Semiconductor superlattices with wide minibands, as proposed by Esaki and Tsu,¹ can show negative differential velocity² due to Bragg reflection of miniband electrons. If an electric field in the region of negative differential velocity is applied along the superlattice axis, a spatially homogeneous field distribution is unstable and traveling high-field domains can be formed exciting current oscillation in an external circuit. The occurrence of traveling domains was concluded from the observation of photocurrent transient oscillations induced in an undoped superlattice by picosecond light pulses,³ and through the microwave emission caused by continuous current oscillation from a doped superlattice.⁴ The frequency of the current oscillation was given by the ratio of the domain velocity and the superlattice length. It was shown⁵ that the oscillation frequency in superlattices with different miniband widths and almost equal length increases almost proportionally to the peak drift velocity, which strongly depends on the miniband width. So far, the highest frequency of 65 GHz has been reported for a superlattices with a miniband width of 72 meV.⁶ In this letter we report on a study of miniband transport in a superlattice (at room temperature) with a much larger miniband width (120 meV) and report on self-sustained current oscillation at a frequency above 100 GHz.

A superlattice (n doped $9 \times 10^{16} \text{ cm}^{-3}$) with 130 periods of 40 Å GaAs and 6 Å AlAs has been grown on a n^+ GaAs substrate by molecular beam epitaxy. A device [Fig. 1(a)] was fabricated on the GaAs substrate consisting of one small-area superlattice mesa ($10 \times 15 \mu\text{m}^2$) and two large-area superlattice mesas ($80 \times 100 \mu\text{m}^2$); the mesas were pro-

vided with ohmic contacts. The substrate was thinned to a thickness of less than 50 μm and its reverse side covered with a Ti/Au layer. The device was glued from the substrate side with silver epoxy on a copper block.

We used a high-frequency (HF) probe (with a signal and two ground probe needles) in order to contact the three mesa elements. Applying a voltage between the contacts of the small-area mesa (signal) and both large-area mesas (ground),

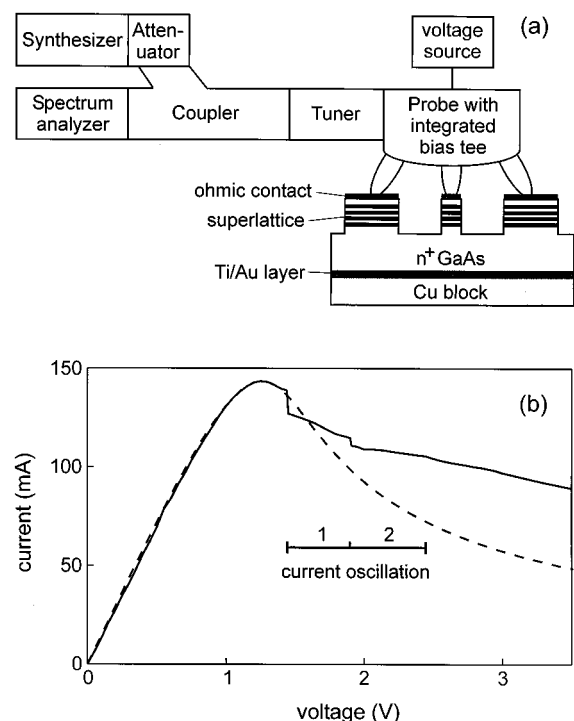


FIG. 1. (a) Experimental setup and (b) I - V characteristic of the active superlattice mesa (solid line) and calculated characteristic (dashed line).

^{a)}Permanent address: Institut für Angewandte und Experimentelle Physik, Universität Regensburg, Universitätsstr.31, 93040 Regensburg, Germany. Electronic mail: ekkehard.schomburg@physik.uni-regensburg.de

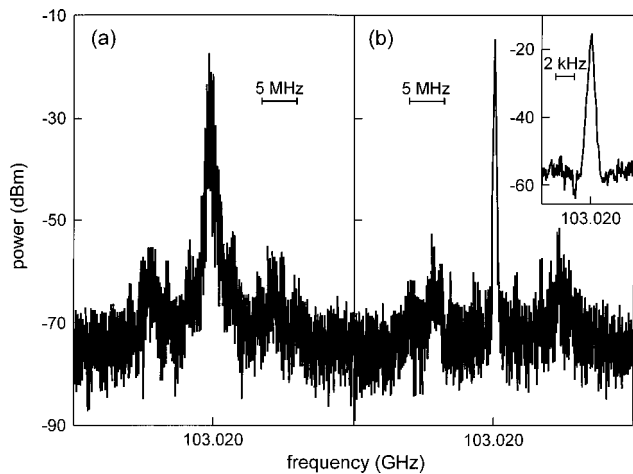


FIG. 2. Microwave spectrum of the free current oscillation (a) and the frequency-locked oscillation (b). Inset: Spectrum of the frequency-locked oscillation measured with high frequency resolution.

a current flow occurred from the signal probe needle through the small-area superlattice (acting as active mesa), the n^+ GaAs substrate and both large superlattices (acting as low series resistance) to the ground probe needles.

The HF probe guided broadband, an electromagnetic wave, excited by the current oscillation in the active mesa, to a rectangular waveguide (75–110 GHz). A three-stub tuner improved the matching between the impedances of the superlattice device and the waveguide. A directional coupler allowed the measurements (with a spectrum analyzer) of microwave radiation and the coupling of an external HF field to the active mesa. A synthesizer with an external attenuator provided radiation within a bandwidth of less than 100 Hz.

The current–voltage (I – V) characteristic [Fig. 1(b), solid line] of the active mesa showed ohmic behavior at small voltages, a current maximum and, at higher voltages, a negative differential conductance (NDC) with current jumps. For the maximum current, a peak current density of about 110 kA/cm² and a peak drift velocity of about 75×10^5 cm/s were estimated. Microwave emission was observed at voltages from 1.4 up to 2.4 V. Between the first and second current jump [marked as region 1 in Fig. 1(b)] broadband emission around 103 GHz (bandwidth several 100 MHz) occurred; after the second current jump [region 2 in Fig. 1(b)] a narrower line was found. The emission line in region 2 [Fig. 2(a)] had a center frequency near 103 GHz with a linewidth of about 1 MHz. By changing the position of the tuner stubs, the output power was optimized. We found a maximum power of about 0.5 mW, which corresponded to a conversion efficiency from direct-current (dc) to HF power of 0.3%.

We attribute the microwave emission to a current oscillation excited by propagating dipole domains. According to a simulation⁵ based on the Poisson equation, the continuity equation, and an Esaki–Tsu drift-velocity field characteristic,¹ a dipole domain forms at the cathode and propagates through the superlattice. Near the anode the domain is quenched, causing a current spike in the external circuit and another domain appears at the cathode. This process periodically repeats leading to a current oscillation with a transit frequency $f \approx 0.7v_p/L$, where $0.7v_p$ is the domain velocity and v_p the peak drift velocity. The frequency ob-

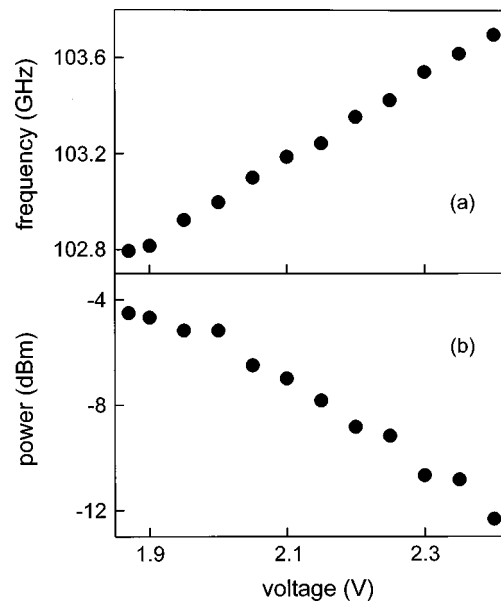


FIG. 3. (a) Tuneability and (b) output power.

served in our experiment is in reasonable agreement with the calculated transit frequency.

An external HF field (power: 100 nW), applied to the superlattice device with a driving frequency close to the oscillation frequency of the superlattice, resulted in a frequency-locked oscillation at the driving frequency. The locking of the oscillation was indicated by a narrow-band microwave emission [Fig. 2(b)] having almost the same power as that observed for the free oscillation. The linewidth of the locked oscillation [inset of Fig. 2(b)] was less than 100 Hz, which is (within the frequency resolution of our spectrum analyzer) equal to the linewidth of the external source. Frequency locking was found within a locking range of about 1 MHz.

The free oscillation in region 2 was almost linearly tunable [Fig. 3(a)] by about 800 MHz. The power [Fig. 3(b)] decreased by about a factor of six over the whole tuning range. At present, we have no explanation for this tuning behavior.

We attribute the transport to free electrons in the lowest superlattice miniband. Using a modified Kronig–Penney model,⁷ we found a miniband width of about 120 meV. We calculated the current–voltage characteristic of the active superlattice mesa using the Esaki–Tsu I – V characteristic,¹ taking into account the electron distribution at 300 K⁸ and both elastic and inelastic scattering.⁹ The I – V characteristic is given by $I = 2I_p V / \{V_c [1 + (V/V_c)^2]\}$, where

$$I_p = enA \frac{\Delta d}{4\hbar} \frac{I_1(\Delta/2k_B T)}{I_0(\Delta/2k_B T)} \left(\frac{v_\epsilon}{v_\epsilon + v_{el}} \right)^{1/2}, \quad (1)$$

I_p is the maximum current, V the voltage, $V_c = \hbar L / (ed\tau)$ the onset voltage of the NDC, n the carrier concentration, e the elementary charge, A the area of the active mesa, Δ the miniband width, d the superlattice period, \hbar Planck's constant, I_0 and I_1 are the modified Bessel function of zeroth and first order, T is the temperature, k_B Boltzmann's constant, $\tau = [v_\epsilon(v_\epsilon + v_{el})]^{-1/2}$ is an average intraminiband relaxation time, v_ϵ the inelastic, and v_{el} the elastic scattering rate. Assuming a series resistance of 5 Ω , the calculated I – V char-

acteristic (Fig. 1, dashed line) gives a good description of the main parameters (I_p , V_c , and small-field conductance) of the experimental curve and also showed an NDC. Our analysis delivered $\tau \approx 150$ fs, $\nu_\epsilon \approx 0.3 \times 10^{13} \text{ s}^{-1}$, and $\nu_{el} \approx 1.2 \times 10^{13} \text{ s}^{-1}$. We suggest that the inelastic scattering at room temperature was due to interaction with optical phonons,^{10,11} while the elastic scattering was caused by the interface roughness between the GaAs and AlAs layers as discussed for other superlattices.^{11,12} For voltages larger than the voltage of the first current jump [Fig. 1(b)] our calculation is no longer valid, because the field along the superlattice is not homogeneous and propagation dipole domains occurred.

We attribute the frequency locking of the current oscillation to a synchronization of the domain propagation in the superlattice by an external HF field. Within a small range of the driving frequency (locking range) the domain velocity was adjusted by the external field leading to a driven transit frequency equal to the driving frequency. Assuming that the linewidth of the free oscillation was mainly determined by fluctuations of the domain formation and propagation, the synchronization would lead to a suppression of the fluctuation, and, therefore, to a drastic decrease of the emission linewidth. Outside the locking range, the external field disturbed the domain propagation by slightly varying the domain velocity in each period causing an emission line with a width comparable to, or larger than, the linewidth of the free oscillation.

Our experiment indicates that the output power of the free oscillation depended on the position of the tuner stubs, i.e., the load impedance delivered to the superlattice device. We believe that an improved impedance matching should lead to a further increase of the output power. However, more experiments are needed to determine the power levels and efficiencies that may be expected from superlattice devices.

In comparison with our superlattice device, a GaAs–AlAs resonant tunneling diode (RTD) oscillator produced an order of magnitude less power ($15 \mu\text{W}$ at 112 GHz)¹³ at about the same efficiency. The output power is limited by the use of RTDs with a small cross section (below $100 \mu\text{m}^2$), which is necessary in order to match the impedance of an RTD (having an I – V curve with a steep slope in the NDC region) to normal circuit impedances (e.g., 50Ω).¹³ Such a limit does not exist for a superlattice device because the NDC occurs over a range of several volts [Fig. 1(b)] making the device impedance much more suitable for matching with an external circuit.

In comparison with a GaAs Gunn diode, a superlattice device can exhibit a current oscillation at a higher fundamental frequency. The negative differential velocity in a Gunn diode is based on electron transfer from a central conduction band minimum to satellite minima: this transfer is character-

ized by electron acceleration and energy relaxation times on the order of 1 ps¹⁴ imposing a fundamental frequency limit of below 100 GHz for a GaAs Gunn device.¹⁴ The superlattice device can be operated at a fundamental frequency above 100 GHz, which is possible due to an order of magnitude shorter average relaxation time (0.15 ps).^{9,15}

In conclusion, we have shown that a GaAs/AlAs superlattice with very thin barriers (2 monolayers) can emit high-frequency radiation with a frequency above 100 GHz and with a high-frequency power of 0.5 mW. The oscillator based on our superlattice device had a much larger output power than available from the best reported GaAs–AlAs RTD oscillator and was operated in a fundamental harmonic mode at higher frequencies than a GaAs Gunn oscillator.

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