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A Planar Gunn Diode Operating Above 100 GHz

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***Abstract*—We show the experimental realization of a 108-GHz planar Gunn diode structure fabricated in GaAs/AlGaAs. There is a considerable interest in such devices since they lend themselves to integration into millimeter-wave and terahertz integrated circuits. The material used was grown by molecular beam epitaxy, and devices were made using electron beam lithography. Since the frequency of oscillation is defined by the lithographically controlled anode–cathode distance, the technology shows great promise in fabricating single chip terahertz sources.**

***Index Terms*—Gunn devices, semiconductor device fabrication, submillimeter wave diodes, terahertz.**

THERE is a growing demand for small, cheap, high-power generation, low-power consumption, and room-temperature operating terahertz sources [1], [2]. Research has investigated both electronic and optical approaches. For example, the quantum cascade laser shows exceptional promise, but operation in the important sub-1-THz regime has not been achieved, and cryogenic cooling is required [3]. A well-known electronic approach is to use negative differential resistance in, for example, a Gunn diode [4]. However, conventional vertical device architectures do not readily permit efficient fundamental-mode operation of vertical Gunn diodes much above 90 GHz in GaAs [5] or 315 GHz in InP [6]. However, recent numerical studies have shown that Gunn diodes are, in principle, capable of operation above 1 THz, provided that they are appropriately engineered [7]. The frequency of oscillation is determined by the time taken for a Gunn domain to form and complete a transit between the cathode and anode contacts. Ideally, it would be possible to grow thin diode structures to obtain high-frequency oscillations in the terahertz regime, but, in practice, this is not achievable due to the limits imposed on domain formation by inadequate electron density and device heating. Typically, electron densities much greater than 10^{16} cm^{-3} are not possible, setting a lower limit of about 1 μm to the anode–cathode length and a frequency limit of approximately 90 GHz for fundamental-mode operation. Even in practice, this is hard to achieve, and hence, most devices are made a little longer and designed to operate at fundamental frequencies of approximately 45 GHz. If higher frequencies are desired, power is extracted by second harmonic operation.

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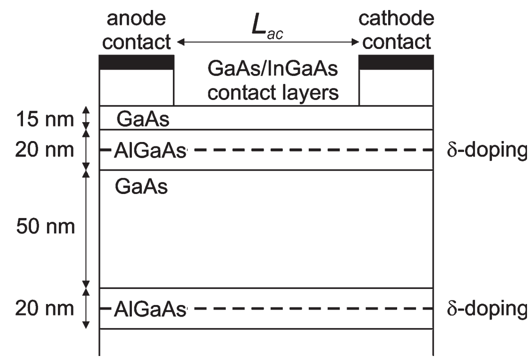

Fig. 1. Layer structure of the planar Gunn diode showing the recess etch between the contacts.

Despite these limitations, the Gunn diodes offer the advantages of being small and relatively efficient, and it is desirable, therefore, to seek device architectures that can give an improved performance. One such architecture is the planar Gunn diode. The most recent example is the field-effect controlled transferred electron device that has been shown to oscillate at frequencies up to 60 GHz in the fundamental mode [8]. These devices closely resemble a modulation-doped field-effect transistor (MODFET), and simulations by Dunn have shown that anomalous behavior in MODFETs can be attributed to the formation of Gunn domains [9].

We have adapted this approach in order to make planar Gunn diodes operating above 100 GHz. The design simulations for this letter were performed using a self-consistent Monte Carlo model employing analytic band structure. The electron density in the channel was on the order of 10^{17} cm^{-3} so that degeneracy effects were not considered. Both dc simulations and simulations with an RF feedback potential were performed which indicated that the efficiency of these devices was similar to those of more traditional vertical structures (about 5% efficiency in the first harmonic mode) but with the ability to operate at much higher frequencies.

A cross section of the device showing its critical features and dimensions is shown in Fig. 1. The semiconductor material was grown by molecular beam epitaxy to match the layer properties specified by device modeling. The surface layer is 15 nm of highly doped n-GaAs followed by 20 nm of undoped $Al_{0.23}Ga_{0.77}As$ layers with δ-doping in the middle with an areal density of 8×10^{11} cm^{-2}. The channel layer is 50 nm of GaAs. Beneath the channel layer, there is a further 20-nm-thick AlGaAs layer that is also δ-doped. The channel layer is estimated to have an electron charge density of $\sim 10^{17}$ cm^{-3}. Multiple graded layers of GaAs/InGaAs layers are grown above the device active regions in order to aid the formation of ohmic contacts. These layers are subsequently removed from the active device area. Device mesas were made by wet etching [10],

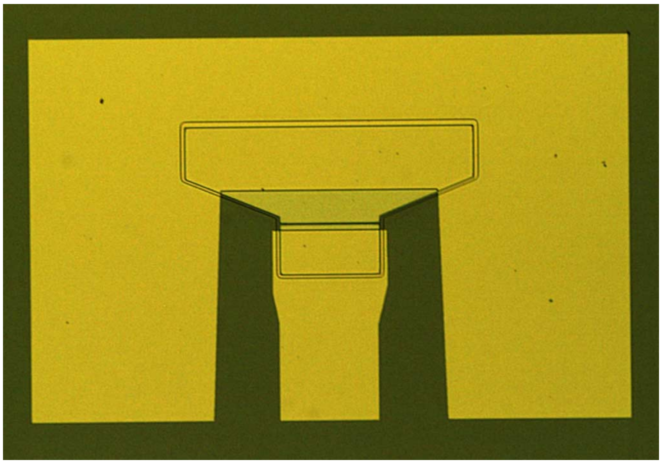

Fig. 2. Optical micrograph of a completed device.

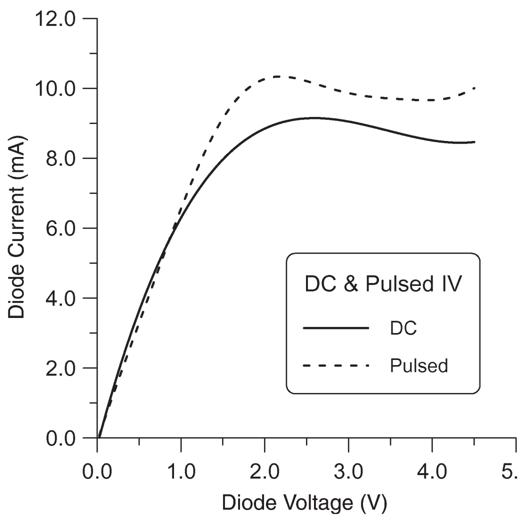

Fig. 3. I–V characteristics of a planar Gunn diode with a 1.3-μm anode–cathode separation. The device width is 60 μm.

followed by fabrication of the ohmic contacts using electron beam lithography [11]. The typical contact resistance after processing was 0.15 $\Omega \cdot$ mm [11]. The final step in the fabrication of the devices was the removal of the unwanted GaAs/InGaAs contact layers above the active region. This was facilitated using an $Al_{0.8}Ga_{0.2}As$ etch stop layer that was inserted during wafer growth [12]. The samples were etched in 3 : 1 citric acid:H_2O_2 (50% w/w citric acid) solution for 20 s. Fig. 2 shows an optical micrograph of a completed device.

Since the ohmic-contact separation is controlled by the lithographic dimensions, we are able, within the limits of process tolerance, to choose the anode–cathode distance (L_{ac}), hence the electron transit distance. The results in this letter are for a device with a L_{ac} of 1.3 μm and a device width of 60 μm. The effective L_{ac} is slightly shorter due to lateral diffusion during the ohmic-contact anneal. In practice, many devices (between 140 and 150) are simultaneously fabricated on the same chip. Prior to making RF measurements, each of the diodes is probed at dc to evaluate their current–voltage (I–V) characteristics. The data were taken using a combined dc and pulsed I–V measurement system (DIVA D210) in order to observe and compare the effect of Joule heating on the device. Fig. 3 shows

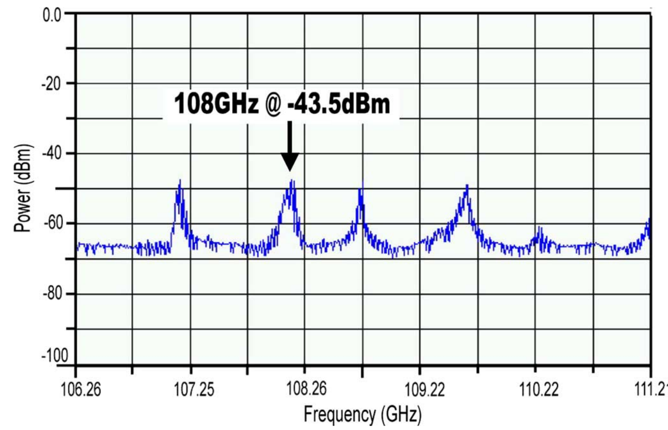

Fig. 4. Spectrum measured from a typical device. The signal at 108 GHz was confirmed to be the real signal. The others are spurious.

a typical I–V plot for one of the devices. We found that the result is highly reproducible. As can be clearly seen, the device is more conductive under circumstances of pulsed stimulus, and there is a negative differential resistance region in the device. The current in the device reaches 10 mA which is equivalent to 1.66 A/mm. These results are comparable to the theoretical data from Monte Carlo simulations and the prior art [9].

The measured spectrum from one of the devices is shown in Fig. 4. The experimental setup uses a 40-GHz Spectrum Analyzer (Agilent 8564EC), the operating range of which has been extended to the W-band using an external mixer (Farran Technology WHMP-10). The dc bias was in the range of 3.5–4.5 V for any oscillation to be seen. The data show a number of tones. The majority of the signals seen arise as a consequence of intermodulation in the external mixer. The analyzer has a signal identification function that enables us to ascertain that the 108-GHz signal is real. The signal is locked to the 18th harmonic of the spectrum analyzer's local oscillator. The signal power is small at present. We attribute this to the narrow width of the device and the fact that no on-chip waveguide has been employed to facilitate impedance matching from the diode to the 50-Ω input impedance of the detector.

Simulation and experimental results from this, and longer devices, indicate a good match to the expression $f_{osc} = v_{mean}/(L_{ac} - L_{dead})$, where f_{osc} is the oscillation frequency, v_{mean} is the mean domain velocity, and the domain transit length is reduced by the dead-space L_{dead}. We observe, by averaging results from simulations of a number of device lengths, that $v_{mean} \sim 10^5\ \mathrm{m \cdot s^{-1}}$, and $L_{dead} \sim 0.30\ \mu$m. This is true for the fundamental-mode operation and is further confirmed when examining the simulation results of the time variation of current or the internal profiles of potential, electron density, or electric field.

In conclusion, we have demonstrated a planar Gunn diode oscillator operating at fundamental frequencies up to 108 GHz. Analysis of devices indicates that frequency is limited by the electron density and the anode–cathode distance. This can be overcome by using a planar architecture. We believe that this is the highest frequency achieved by a planar Gunn diode using an AlGaAs/GaAs quantum-well structure on a GaAs substrate. The new device will enable simpler MMICs for a wide range of military and civilian applications [13]. Simulations indicate that the planar Gunn diodes have the potential to extend their range of operation up to 0.5 THz in the fundamental mode (1 THz in the second harmonic) [14] and will therefore be of use in the terahertz systems.

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