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Multi-Channel GaAs-based Planar Gunn Diodes

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Abstract— **We present a multi-channel GaAs-based planar Gunn diode. By introducing extra channels, the output RF power has been significantly improved compared to single-channel GaAs-based planar Gunn diodes. For a 1.14 µm length and 60 µm wide device, the highest power achieved was approximately -4 dBm operating in fundamental mode at 109 GHz, and -26.6 dBm at its second-harmonic at 218 GHz.**

Keywords—Millimeter-Wave Solid State Devices, Gunn Diode,

I. INTRODUCTION

PLANAR Gunn diodes with GaAs/AlGaAs heterojunctions have successfully demonstrated oscillation in the transit-time fundamental mode at 108 GHz [1]. However, initially reported devices suffered from low output RF power e.g. -43.5 dBm at 108 GHz. Although techniques, such as introducing extra delta doping to enhance electron density in the channel and therefore better formation of Gunn domains, or embedding the diodes into resonant circuits have been applied, a relatively weak output RF power e.g. –28 dBm at 116 GHz was achieved [2]. The DC-to-RF conversion efficiency remains far lower compared to conventional vertical Gunn diodes [3]. It has been shown that the frequency of oscillation that can be achieved using a vertical Gunn diode is limited by the free carrier density in a thin solid layer of GaAs and the anode-cathode separation that is defined by the thickness of the layer. However, a point is reached in a given material where the higher densities become infeasible due to a range of effects which combine to significantly reduce the device lifetime. For this reason modern devices often operate in a non-fundamental mode of operation [4] with an associated reduced efficiency. Using a planar structure it is possible to use modulation doping to make an accumulation layer or 2D electron gas (2DEG) with very high electron density. Electron transport in the plane of the 2DEG can then be unimpeded by energy barriers, as would be the case for vertical transport through such a layer structure and an anode-cathode spacing of less than 2 µm can be used. The availability of sophisticated layer structures makes planar Gunn diodes an excellent candidate for future source technologies [5].

In this paper, we demonstrate that by introducing additional channels, higher output RF power and DC-to-RF conversion efficiency can be achieved from a GaAs-based planar Gunn diode at frequencies above 100 GHz.

II. DEVICE FABRICATION

Molecular beam epitaxy was used to grow layers on a 620 µm thick semi-insulating GaAs substrate. A 0.5 µm GaAs buffer layer was grown first on the substrate, followed by a 20 period GaAs/AlGaAs superlattice. The active part of the device consisted of seven channels and each individual channel was made of 50 nm undoped GaAs that was sandwiched by a 20 nm double δ-doped $Al_{0.23}Ga_{0.77}As$ layer. 15 nm of highly doped GaAs was grown on top of the $Al_{0.23}Ga_{0.77}As$ barrier layer to avoid oxidation. This was followed by a 5 nm $Al_{0.8}Ga_{0.2}As$ etch stop layer doped at 4×10^{18} cm^{-3}. The top of the wafer was finished with multiple graded layers of GaAs/InGaAs to facilitate good Ohmic contact formation. Fig. 1 shows a schematic of the epitaxial layer structure of the device.

For the device terminals, anode and cathode contact regions were defined by electron beam lithography using polymethylmethacrylate (PMMA) resist. Pd/Ge/Au/Pt/Au metal was deposited by e-beam evaporation followed by lift-off. The contacts were then annealed at 400 °C for 60 s in a rapid thermal annealer. A mesa was etched using 1:1:10 H_2O_2:H_2SO_4:H_2O for ~150 seconds at an etch rate of 60 nm/s. A 50 Ω coplanar waveguide (CPW) feed structure was then deposited using 200 nm gold to form the probe pads for subsequent on-wafer RF and dc measurements. The CPW had a ground-to-signal separation of 40 µm and a central signal track width of 60 µm. Finally, the unwanted multiple graded layers of GaAs/InGaAs were etched away by dipping in citric acid:H_2O_2 solution for 30 seconds using the 5 nm AlGaAs etch stop layer.

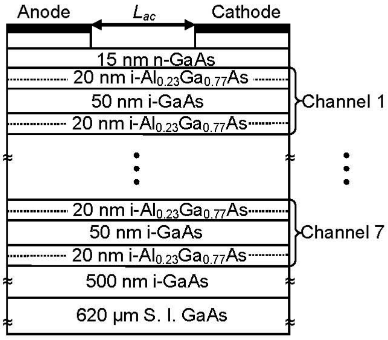

Fig. 1. A schematic of the layer structure of the seven-channel device. The dashed lines indicate δ-doping with an area density of 8×10^{11} cm^{-2}.

III. EXPERIMENTAL RESULTS

Direct current and pulsed current characteristics of the devices were measured with a semiconductor device analyzer

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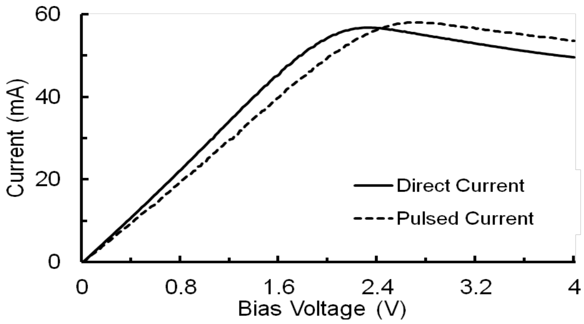

Fig. 2. DC and pulsed *I-V* characteristics of a 7-channel planar Gunn diode with L_{ac}=1.14 µm.

(Agilent Technologies B1500A) on a semi-automated probe station (Cascade Microtech Summit 12K). For pulsed *I-V* measurement, the pulse width and period was set to 0.5 ms and 50 ms, respectively. It can be clearly seen in Fig. 2 that the pulsed *I-V* has higher negative differential region (NDR) peak voltage, V_{pk}, of 2.5 V and higher peak current, I_{pk}, of 58.0 mA. Due to the bias associated heating effect, the dc *I-V* curve has V_{pk} = 2.3 V and I_{pk} = 56.8 mA. The current densities are very close to HEMT devices of similar width at zero gate bias with typical source-drain currents of approximately 900 mA/mm [6]. This level of current density is approximately 5 to 6 times higher than that of a single-channel planar Gunn device [1].

The RF performance of the device was measured using a spectrum analyzer (Agilent Technologies E4448A) and two different external sub-harmonic mixers (Farran Technology WHMP-10 and WHM-05) to cover both the fundamental and second-harmonic frequency bands up to 220 GHz. Additional S_{11} measurements were carried out on the diodes using an Agilent NC5250 PNA vector network analyser operating from 500 MHz to 220 GHz to verify the fundamental mode [2]. Devices were biased at 3.2 V that was 1.3 times higher than the bias threshold voltage V_{pk} at which the onset of NDR occurred, to ensure stable oscillation.

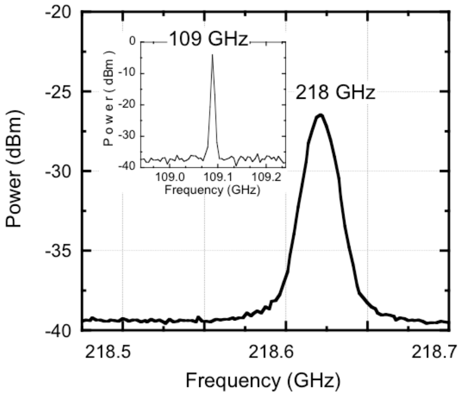

Fig. 3. The second harmonic spectrum of a 7-channel GaAs-based planar Gunn diode with L_{ac}=1.14 µm and width 60 µm. The measured power at 218 GHz is -26.6 dBm after taking into account losses from the measurement setup. Inset show -4dBm power at 109 GHz fundamental from the same device in W-band.

A device with L_{ac}=1.14 µm was measured in the fundamental mode of oscillation at *W*-band using the WHMP-10 mixer. After the oscillation frequency and power were identified on the spectrum analyzer, the output power level was further confirmed using a power meter (HP 8563) with a calibrated *W*-band sensor. After accounting for the insertion loss from the probe (Cascade Microtech ACP110-GSG-100) of 2.8 dB, the highest power directly measured from the device in its fundamental oscillation mode was -4 dBm at 109 GHz.

The second-harmonic oscillation of the device was measured in the *G*-band using the WHM-5 mixer. The bias current for the *G*-band mixer was optimized to achieve its best conversion loss performance. The measured spectrum of the proposed device in its second-harmonic oscillation mode is shown in Fig. 3. For the second-harmonic measurement system insertion loss was estimated to be 59 dB that includes 55 dB conversion loss from the external mixer and 4 dB insertion loss from the on-wafer probe and cable. The actual RF power for the second-harmonic oscillation was therefore estimated to be -26.6 dBm at 218 GHz. The difference between the fundamental and the second-harmonic oscillation power level is about 22 dB. This difference has previously been seen in devices with long L_{ac} operating at lower frequencies [4]. The seven-channel planar Gunn diode has shown significant improvement in RF power as compared to single quantum well device [1]. This is attributed to improved domain formation in the buried quantum wells that are less sensitive to surface conditions than is the case with a single quantum well device.

IV. CONCLUSION

In conclusion, we have demonstrated a 7-channel GaAs-based planar Gunn diode generating output RF power of -4 dBm in its transit-time fundamental mode of oscillation above 100 GHz, and -22.6 dBm in its second-harmonic oscillation mode at 218 GHz. The proposed multiple-quantum well planar Gunn diode with a higher level of output power shows great potential as a solid-state source of millimeter-wave and sub-terahertz radiation.

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