Novel Planar Gunn Diode Operating in Fundamental Mode up to 158 GHz

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Abstract. We show the experimental realisation of fundamental mode operation of planar Gunn diode structures fabricated in GaAs/AlGaAs quantum wells. The electron density in the active channel is enhanced by positioning double delta-doping layers on either side. Small signal measurement shows that a typical device exhibits negative resistance up to 158 GHz. Using this device structure we have demonstrated a planar Gunn oscillator working at 115.5 GHz with an output power of -28 dBm.

1. Introduction

Gunn diodes have been studied as a source of stable and low-noise solid-state microwave radiation since the early 1960s. Most research work on Gunn diodes has concentrated on “vertical” structures, but relatively few researchers have explored “planar” architectures. Recent research indicates vertical Gunn diodes can work up to sub-Terahertz frequency range. Among these, InP-based vertical Gunn diodes have shown second harmonic oscillation at a frequency of 425 GHz [1] and simulations suggest GaN-based vertical Gunn diodes may possibly produce even higher frequency fundamental-mode oscillation [2]. However, almost all vertical Gunn diodes are embedded in bulky cavities and the RF power is extracted from regular rectangular waveguide, leading to higher cost and difficulty with integration to modern MMIC technology. Although some researchers have reported “planar” Gunn devices [3, 4], they are in fact still “vertical”, because current flow is perpendicular to the epitaxial layers in the devices. Recently, a “true” planar GaAs-based Gunn diode has successfully been demonstrated at 108 GHz [5]. The device has a HEMT-like structure but without a gate. This novel technology also has the potential to permit the fabrication of different devices with different oscillating frequencies on the same wafer, because the frequency of the diodes is determined by lithographically controlled anode and cathode separation. This opens up new possibilities for complex monolithic circuit designs.

In this paper, we present recent work on planar Gunn diodes. The devices are fabricated on to an electron rich inversion layer. The electron density in the inversion layer places a limit on the maximum achievable operating frequency since there is anode-cathode region must be long enough for Gunn domains to form. In this work we present devices into which an additional delta-doping layer on each side of the active channel has been implemented. As these additional delta-doping layers increase the electron density within the active layer, it becomes possible to form satisfactory Gunn
domains within a shorter transit region. This design has made it possible to experimentally observe improved performance. Typical devices exhibit negative resistance up to 158 GHz and output power of -28 dBm has been extracted at a frequency of 115.5 GHz. This frequency is the highest recorded from GaAs-based planar Gunn diodes for the fundamental mode of oscillation.

2. Fabrication and measurements of planar Gunn diode

The semiconductor material was grown by molecular beam epitaxy to match layer properties specified by device modeling [6]. Figure 1a is a schematic view of the device. Metal alloys (Pd/Ge/Au/Pd/Au) were deposited on the top of multiple graded layers of GaAs/InGaAs in order to aid the formation of low resistance contacts (approximately 0.15 Ω·mm). Beneath the contact layers there a 15 nm layer of highly doped n-GaAs was incorporated. The thickness of this layer was optimized by Monte Carlo simulation [6]. Below it is a 20 nm barrier layer that is un-doped Al_{0.23}Ga_{0.77}As. Two δ-doping (8 × 10^{11} cm^{-2}) layers were inserted evenly in this layer during growth. The channel layer was made of 50 nm un-doped GaAs. Another 20 nm Al_{0.23}Ga_{0.77}As layer with two δ-doping (8 × 10^{11} cm^{-2}) barrier was grown under the channel layer. The channel layer was estimated to have an electron charge density of the order of approximately 10^{17} cm^{-3} [8, 9].

![Figure 1.](image1)

Figure 1a shows the optical image of a planar Gunn diode embedded in a co-planar waveguide (CPW) in order to allow for RF measurements. Small-signal measurements on individual planar Gunn diodes were carried out using similar techniques to those that have previously been used to characterise vertical Gunn diodes [3] and other similar one-port active devices e.g. IMPATT diodes [7]. The measurement setup was based on two sets of PNAs (Agilent) covering the frequency range from DC to 110 GHz and 140 to 220 GHz. Both sets of PNAs used GSG 100 µm-pitch probes that were supplied by GGB industries. The calibration substrates (Microtech technology) were 109-102B for DC-110 GHz and CS-15 for 140-220 GHz, respectively.

Figure 2 shows the small-signal measurement results after the diode was de-embedded from CPW measuring pads over the frequency range of 140-160 GHz. It can be seen from Figure 2a that the reflection coefficient (S_{11}) of the planar Gunn diode is over 0 dB up to 158 GHz when the bias is 2.8 V; it means the power reflected from the diode is greater than the power incident on it. This demonstrates that the diode generates RF power up to 158 GHz. This directly leads to a negative resistance for the diode, as seen in Figure 2b, according to the following equation

\[ Z_{11} = \frac{1 - S_{11}}{1 + S_{11}} \cdot Z_0 \]

where \( Z_0 = 50 \Omega \). With appropriate design of external circuits [7], an oscillator working over 150 GHz may be achieved.
3. Planar Gunn Oscillator

On the same wafer we constructed a planar Gunn oscillator. Since most Gunn diodes are embedded in resonant circuits in order to improve their frequency stability and tunability [1, 4]. We also designed a simple CPW resonator to operate at the frequency at which the planar Gunn diode may oscillate. The circuit layout is shown in Figure 3a. It was drawn in L-edit (Tanner EDA) for smooth connection with e-beam fabrication process. The circuit was optimised by commercial FEM (Finite Element Method)-based software HFSS (Ansoft) and the simulation result is shown in Figure 3b.

The oscillator contains two 1.3 μm (anode-cathode distance) planar Gunn diodes and an open-end coplanar waveguide. The two diodes were placed back-to-back in parallel in order to make it a two-port device and to easily integrate with the CPW resonator. The left end of CPW signal line was left open to permit the application of a DC bias to the diodes. However, the gap had to be kept small enough to make the circuit behave as a short-circuited at the frequency of interest so that the diodes could sit where the maximum electric field appeared on the waveguide. The right end was left fully open to enable on-wafer probing. By using HFSS, the optimal geometry of the circuit was finalized as shown in Figure 3a and the resonant frequency of this circuit is 115.36 GHz as shown in Figure 3b.

Once the device was fabricated, its output power and oscillation frequency were measured. The measurement setup consisted of 100 μm-pitch W-band GSG probe, W-band harmonic mixer (WHMP-10 from Farran Technology) and Spectrum Analyzer (E8364B from Agilent). The output power has been corrected from conversion loss induced by the mixer and other systemic losses from cables and
probe. Figure 4 illustrates the oscillator produced -28 dBm at 115.536 GHz which is very close to the resonant frequency of the circuit.

![Figure 4. The oscillator produces -28 dBm output power at 115.5 GHz after corrections. The mixer has conversion loss of 28 dB from manufacture’s datasheet. Other losses from cables and probe contribute about 2 dB. This signal is confirmed to be the fundamental mode of oscillation. Note: the central peak is the real signal and other peaks are spurious.]()