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Two-Terminal InGaAs Microwave Amplifier

Hanbin Wang, Yifei Zhang, *Member, IEEE*, Yanpeng Shi, Haotian Ling, Qingpu Wang, Fengqi Liu, Fuhua Yang, Kunyuan Xu, Qian Xin and Aimin Song, *Senior Member, IEEE*

Abstract—The feasibility of using a two-terminal InGaAs planar Gunn structure as a microwave amplifier is proposed and verified. By achieving a pronounced negative differential resistance with a peak-to-valley current ratio of 1.20, our devices are able to amplify microwaves at a high gain of 17 dB. Compared to commonly used three-terminal transistor-based microwave amplifiers, the proposed devices not only have a simple structure but also are capable of achieving high operating frequencies even with relatively large feature sizes. The device with a channel length of 4 μm has a positive gain up to about 77 GHz, and the 2- μm device is able to amplify microwaves well beyond 110 GHz. Furthermore, the planar Gunn amplifier shows a good linearity over a wide input power range from -45 to about 0 dBm. A good operation stability has also been demonstrated despite having no substrate thinning and heat sink.

Index Terms—Gunn amplifiers, Microwave devices, Negative differential resistance, Stability

I. INTRODUCTION

SOLID-STATE power amplifiers that operate at microwave and terahertz (THz) frequencies have a wide range of applications, such as radio astronomy, broadband

wireless communications, radar, medicine imaging, and security inspection [1], [2]. Amplifiers at such high frequencies are typically based on high electron-mobility transistors (HEMTs) on indium phosphide (InP) substrates with channel lengths reduced to tens of nanometers and mushroom-shaped gate [3]. The small channel lengths impose huge challenges in terms of device fabrication and cost, restricting their applications [4]. Though heterojunction bipolar transistors (HBTs) do not rely on nano-scale channels, their high thermal density and sensitivity to high temperatures affect their performance in high-power and heavy load conditions [5]. Prior to the use of transistors, two-terminal devices with negative differential resistance (NDR) in their current-voltage (I-V) characteristics were actually the first solid-state devices for power generation and amplification at microwave frequencies [6]. Although two-terminal amplifiers, such as impact ionization transit-time diodes and resonant-tunneling diodes, have advantages of simple structures and high working frequencies, their impedances are typically strongly dependent on the input power, which limits their high-power applications due to nonlinear distortion [7]-[9]. In contrast, Gunn-diode-based amplifiers show fairly stable impedances and have gained much attention for microwave applications. A Gunn diode may exhibit NDR at high biases due to electrons gaining enough energy to transfer to higher energy valleys within the conduction band. By doing so, the electrons not only lose their kinetic energy to gain higher potential energy but also will have much higher effective mass in the upper valley, hence resulting in a significant reduction of velocity. When biased in the NDR region, the device becomes an active component and microwave signals can be amplified. Compared with other microwave amplifiers, Gunn devices have advantages of simple structure, low cost, high operation frequency, high gain, and low noise [10], [11]. A power gain of 35 dB has been achieved at a working frequency of 94 GHz [12]. However, the device structure of traditional Gunn devices is vertical, which does not permit efficient fundamental-mode operation at frequency higher than 200 GHz [13]. The Joule heating in vertical Gunn diodes caused by the enormous current density can generate a channel temperature as high as 200 °C [14]. The high current density and high channel temperature make it very challenging to fabricate suitable ohmic contact. Furthermore, in order to increase the working frequency, the channel length of Gunn device should be reduced, which requires the doping density in the channel to increase proportionally [10]. As such, the heating effect rapidly escalates in short channels, which may easily lead

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Fig. 1. (a) Cross-section of the InP substrate, and (b) SEM image of a fabricated planar Gunn amplifier with a channel length of W .

Fig. 2. I - V curves of devices with different channel lengths measured a pulse width of 5 ms.

to breakdown. A number of unusual techniques have to be utilized to overcome this issue, including thinning the substrate down to 2 μm and mounting chips on diamond heat sinks, and yet, to the best of our knowledge, the highest fundamental oscillation frequency of InP vertical Gunn diodes is only 160 GHz to date [15]–[17].

In contrast, planar Gunn devices, where the current flows essentially within a very thin two-dimensional (2D) channel, do not suffer a significant Joule heating problem because the current density is much smaller than that in vertical devices, where the current flows through a three-dimensional (3D) bulk channel with a height much smaller than the width. The measured channel temperature of a planar Gunn diodes working in continue wave mode without using any cooling techniques is below 100°C [18]. Another advantage of planar structure is that the channel length does not depend on the epitaxial structure of material, but only on the device geometry. This makes it possible to manufacture diodes with different working frequency in one chip. In addition, the planar structure has much smaller parasitic capacitances, which enables higher working frequencies. Progresses of planar Gunn devices have been remarkable in recent years. The fundamental oscillation frequency of planar Gunn diodes has reached 300 GHz [19], which is approximately twice of that of vertical Gunn diodes. Monte Carlo simulation indicates a possible oscillation frequency up to THz region [20], [21], showing a great potential for planar Gunn devices in terahertz applications. However, so far most of planar Gunn devices have been demonstrated only as oscillators. Here, by achieving a pronounced NDR, we are able to show that planar Gunn diode can also be used as a microwave amplifier. Devices with different channel lengths were fabricated and their DC characteristics, microwave amplification performance, and operation stability were studied.

II. EXPERIMENTAL PROCEDURE

The planar Gunn amplifiers were fabricated on InGaAs channel layer grown by molecular-beam epitaxy (MBE) on InP

Fig. 3. Power gain of planar Gunn amplifiers of different W (a) from 6 to 67 GHz and (b) from 75 to 110 GHz. (c) The peak gain frequency as a function of the reciprocal of channel length. The dashed line is a linear fit.

wafer including a 300 nm $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ buffer layer, a 300 nm InGaAs channel layer, and a 200 nm InGaAs cap layer. The doping density (N_D) of the channel layer is $8 \times 10^{16} \text{ cm}^{-3}$ to make sure $N_D L_c > 10^{12} \text{ cm}^{-2}$ [22]. The cap layer was doped at $2 \times 10^{18} \text{ cm}^{-3}$. Fabrication started with wet etching to define mesa and channel. As shown in Fig. 1(a), three different channel lengths (L_c), i.e., 2, 4, and 6 μm , were investigated. The Ohmic contact, consisting of Pd/Ge/Au/Ti/Au, was deposited using electron-beam evaporation. The contact resistance is 0.35 $\Omega \cdot \text{mm}$. Finally, co-planar waveguide (CPW) was formed using evaporated Ti and Au. A colored scanning-electron microscope image of device is shown in Fig. 1(b). The width of channel (W) is 100 μm . All patterns were defined by electron-beam lithography (EBL) with Poly (methyl methacrylate) (PMMA, molecular weight 950K) resist.

III. RESULTS AND DISCUSSION

Similar to other types of two-terminal amplifiers, Gunn-device-based amplification is based on negative differential conductance (NDC, the reciprocal of NDR) [23]. As shown in Fig. 2, pronounced NDC can be observed in the I - V characteristics of planar Gunn amplifiers measured in pulsed mode. The pulse width is 5 ms, and the period is 200 ms. The peak NDC of devices with $L_c = 4$ and 6 μm is -32.2 mS and -156 mS, respectively. The device with $L_c = 2 \mu\text{m}$ shows a much smaller NDC than the longer devices, and its current starts to increase soon after the NDR region appears at about 1.5 V. This should be mainly attributed to a relatively large series resistance in the short-channel device [24]. The measured series resistance is 4 Ω , which accounts for 30% of the total resistance of the 2- μm device. Thus, NDC will be reduced or totally vanished by large series resistance [25], [26].

Current peak-to-valley ratio (PVR) is one of the key parameters of NDR-based amplifying devices that determines the DC to RF conversion efficiency (η). The relationship can be

expressed as

$$\eta = \frac{(PVR-1)(\beta-1)}{(PVR+1)\beta} \left(\frac{8}{\pi^2} \right), \quad (1)$$

where β is the ratio of DC bias to threshold voltage [27]. The measured PVR of the 4 μm device is 1.20. To the best of our knowledge, this is the highest measured PVR in InGaAs planar Gunn devices with similar dimensions. The high PVR may be attributed to the InAlAs buffer layer and high quality of the semiconductor layers epitaxially grown by MBE. The buffer provides a high degree of layer homogeneity and high-quality interfaces with fewer electron scattering under high electric field so that the electrons can obtain high energy to transfer to the higher energy valley, inducing a pronounced NDR.

RF characteristics of planar Gunn amplifiers were investigated from 6 to 110 GHz using a vector network analyzer (VNA). VNA generates a RF signal to the device under test and measures the ratio of the reflect power to the input, i.e., power gain of two-terminal devices. Figures 3(a) and (b) present power gain of the fabricated devices with different channel lengths. All devices show good power amplification performance. The maximum power gain of devices with $L_c = 6$, 4, and 2 μm is 10 dB at 31.0 GHz, 15 dB at 47.8 GHz, and 4.5 dB at 97.6 GHz, respectively, and their 3-dB bandwidth is 12.6, 5.2, and 35.0 GHz, respectively. Power gain and bandwidth of the devices can be further improved by using matching networks [28].

It can be seen in Figs. 3(a) and (b) that devices with short channels can work at high frequencies. In order to reveal the relationship between the frequency of peak gain and channel length, the peak frequency is plotted as a function of the reciprocal of the channel length in Fig. 3 (c). The dotted and dashed lines represent the measured results and a linear fitting, respectively. Their good agreement indicates an expected linear dependence. The slope of the fitted line is 2.0×10^5 m/s, which matches well with the room-temperature saturation drift velocity of InGaAs [29]. This is consistent with the relationship between oscillation frequency and channel length in planar Gunn diode [25]. Based on this, the working frequency of planar Gunn amplifiers can be predicted to reach 300 GHz, if the channel length is reduced to 0.6 μm , i.e., about ten times that of HEMT amplifiers at the same frequency [30]. This significantly eases the challenges to fabricate extremely small HEMT based microwave amplifiers, particularly for upper band of microwaves and terahertz signals.

Figure 4(a) shows the relationship between the power gain and input signal power. Measurements were performed on a 4- μm amplifier at 45 GHz under biases of 2.9 and 4.0 V. Both curves show good power stabilities with input power up to -5 dBm. The input power level at which the gain drops by 1 dB from the small signal value is commonly defined as 1-dB gain compression point. The 1-dB compression point of device is 0 dBm at 2.9 V with a power gain of 7 dB, and -5 dBm at 4.0 V with a power gain of 13 dB. These are comparable to the previously published vertical Gunn amplifiers [11], [31]. The dashed line rectangles in Fig. 4(a) represent the linear amplifying regions.

Fig. 4. (a) Measured power gain of planar Gunn amplifier as a function of input signal power with different DC biases. (b) Stability test of a 4- μm device at room temperature for two hours.

Thermal stability is another important issue to evaluate power amplifiers. Figure 4(b) shows the power gain of a 4 μm device measured at 47 GHz in pulse mode for two hours with pulse width and pulse period is 65 ms and 2 s, respectively. The average power gain is 16 dB with fluctuation less than 0.8 dB. Considering that no cooling technique has been applied, this result indicates that the planar Gunn amplifier is much more robust than the traditional vertical Gunn devices in which substrate thinning and heat sink are common necessities.

IV. CONCLUSION

In summary, two-terminal InGaAs planar Gunn amplifiers have been demonstrated for the first time. Pronounced NDR and high power gain were observed in 4 and 6 μm devices. Operating frequency up to 110 GHz were realized in the device with a channel length of 2 μm . The experimental results indicate that the peak-gain frequency is inversely proportional to the channel length. Despite having no substrate thinning, heat sink, and other cooling conditions, the amplifiers show robust thermal stability. Due to the advantages of simple fabrication, low cost, high frequency, high gain, and wide linear-power-gain range, the two-terminal amplifiers may find useful applications at microwave and terahertz frequencies.

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