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InP-Based Gunn Diodes with Stable Depletion Layer for W-Band Waveguide Oscillator Applications

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Abstract: In this study, we demonstrated the InP-based Gunn diode for W-band waveguide oscillator application. The fabricated InP-based Gunn diode has a Stable Depletion Layer (SDL) nn^+ structure for low operating currents, high output power and high dc-to-RF conversion efficiency. The 94 GHz waveguide oscillator was also developed in order to demonstrate the RF characteristics of the packaged InP-based Gunn diode. When the anode diameter of InP-based Gunn diode was 60 μm, typical values of oscillation frequency and output power were 94.25 GHz and 16.11 dBm with a dc-to-RF conversion efficiency of 1.6%, respectively, at dc bias of 9 V. The highest output power of 19.1 dBm was obtained with a dc-to-RF conversion efficiency of 2.5% at dc bias of 11 V. The measured phase noise was <-102.9 dBc/Hz at 1 MHz offset with 10 kHz of resolution bandwidth.

Key words: InP Gunn diode, stable depletion layer, W-band, waveguide, oscillator, output

INTRODUCTION

Many applications in millimeter-wave and submillimeter-wave regions require compact solid-state local oscillators that provide coherent and adequate power level. A well-known approach is to use IMPATT and Gunn diodes with negative resistance. IMPATT diode is known for high noise (Panda *et al.*, 2001) and hence a more suitable choice is Gunn diode. The Gunn diode's low phase noise, moderate output power, reliable long-term operation and relatively low cost, compared to MMIC (microwave monolithic integrated circuit) solution, make it ideal for many applications such as millimeter-wave image sensor and FMCW (frequency modulated continuous wave) radar (Amir *et al.*, 2008).

In this means, oscillators based on GaAs-based and InP-based Gunn diodes have been widely used for millimeter-wave and submillimeter-wave applications. They have proved to be reliable with excellent amplitude and phase noise characteristics. For high frequency operation, the principal limiting factor is a semiconductor material itself because the Gunn effects is directly related to the band structure and the material properties of the semiconductor (Panda *et al.*, 2009). GaAs-based Gunn diodes are normally limited around W-band (75~110 GHz) whereas InP-based Gunn diodes have been shown to generate considerable power level up to submillimeter region. That is why there are increasing demands for development of InP-based Gunn diodes, although GaAs-based Gunn diode has advantage such as cost and process capability compared to InP-based Gunn diode. Besides InP-based Gunn diode shows higher output power level compared to those of GaAs-based Gunn diode.

Early studies for active region doping profile concentrated on conventional n^+nn^+ structures such as uniform doping (Friscourt and Rolland, 1983), graded doping (Eisele and Haddad, 1995) and notch doping structure (Judaschke, 2000). Recently, however, most InP-based Gunn diodes employ lattice-matched InGaAs or Stable Depletion Layer (SDL) nn^+ structure. These structures can improve the performance considerably compared to conventional n^+nn^+ structures. Lattice-matched InGaAs-InP Gunn diodes have complex epitaxial structure (Khalid *et al.*, 2013) whereas SDL nn^+ type Gunn diodes have relatively simple epitaxial structure. SDL nn^+ Gunn diodes have a different mode of operation due to presence of nn^+ structure with low barrier non-ohmic cathode (Zybura *et al.*, 1996). They often are preferred for low operating currents, lower operating temperature, higher efficiency and commercial availability.

In this study, we present the development of InP-based Gunn diode with SDL nn^+ structure, which

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exhibit a high output power and efficiency characteristic. Also, we present the 94 GHz waveguide oscillator using the fabricated InP-based Gunn diode for demonstration of possibility as a power source in millimeter-wave and submillimeter-wave regions.

MATERIALS AND METHODS

Inp-based gunn diode

Epitaxial structure: A physical configuration of the designed and fabricated InP-based Gunn diode is shown in Fig. 1. An integral heat sink is used to facilitate die packaging and InP mesa layer is sandwiched between a bottom integral heat sink and a top contact. The epitaxial structure for InP mesa was grown by Molecular Beam Epitaxy (MBE) techniques. The InP mesa layer consists of a n type InP active layer which is adjacent to the integral heat sink, a n^+ type InP buffer layer and n^+ type InP substrate. Low barrier non-ohmic contact at cathode makes the depletion layer in n type InP active region. As a result of cathode depletion, InP-based Gunn diode operates in a Stable Depletion Layer (SDL) mode, characterized by an oscillating stable depletion layer which serves to restrict current flow. The n type InP active layer is doped to 1.1×10^{16} cm^{-3} with a thickness of 1.8 μm and the n^+ type InP buffer layer is doped to 1.1×10^{18} cm^{-3} with a thickness of 1.5 μm. Gunn diodes with nn^+ structure exhibit much lower current density, higher output power and superior frequency stability with temperature variation, than those of conventional n^+nn^+ structure.

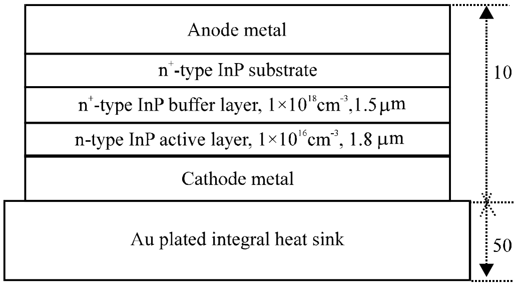

Fig. 1: Physical configuration of the InP-based Gunn diode (not to scale)

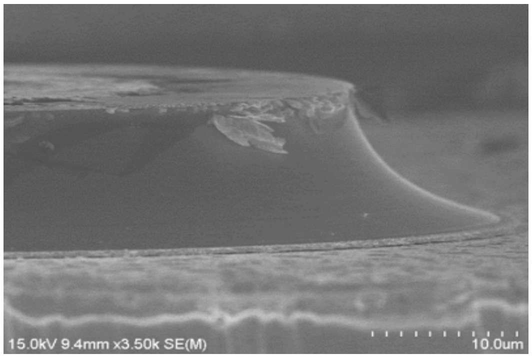

Fig. 2: SEM photograph of the side wall profile with $FeCl_3$-based wet etching

Device fabrication: The InP-based Gunn diodes were fabricated using a front-side trench, cathode ohmic metallization, integral heat sink formation, support layer formation, wafer thinning, anode ohmic metallization, mesa etching and stripping of a support layer. The front-side trench was formed by wet chemical etching using HF:HBr (1:5) mixed etchant. AuGe/Ni/Au (80/27/120 nm) metal system was used for cathode ohmic contact and evaporated by an electron beam evaporator. The contact was annealed in N_2 ambient at 320°C for 60 sec in order to decrease the contact resistance. A SU-8 50 negative photoresist was used for patterning of integral heat sink. The integral heat sink with a thickness of 50 μm was formed by Au plating. After a formation of Au support layer with a thickness of 60 μm, a back-side of wafer was thinned by mechanical lapping and polishing in order to achieve a wafer thickness of 10 μm. AuGe/Ni/Au metal system was evaporated for anode ohmic contact and then it was annealed under the same conditions as the cathode ohmic contact. Then, mesa etching was performed by Cl_2-based dry etching and $FeCl_3$-based wet etching for an isolation of devices. The combined mesa etching method caused an improved oscillation characteristics compared to those of only dry-etched or only wet-etched devices (see the later discussions). Finally the Au support layer was stripped by mixed etchant of HNO_3:HCl (1:3).

A commonly used technique for a mesa etching in InP-based Gunn diode is a $FeCl_3$-based photochemical etching. $FeCl_3$-based wet etching caused black indium on the etched surface which disturbs an etching process. Therefore a process for removing black indium using Br-based etchant, Br_2:HBr:H_2O (1:18:81) is required. Although this wet etching method has advantages such as process simplicity and low process price, there are drawbacks to this method, these are over-etching and poor side wall profile of mesa layer. The amount of over-etching is often uncontrollable and limits the uniformity of mesa layer. Poor side wall surfaces directly degrade device performance, especially with regard to breakdown voltage and power transfer efficiency. The SEM photograph of poor side wall profile with $FeCl_3$ light enhanced wet etching is shown in Fig. 2.

Another method for mesa etching is dry etching by Inductively Coupled Plasma Reactive Ion Etching (ICP-RIE) system with Cl_2:CH_4:H_2 (7:8:6) plasma, ICP

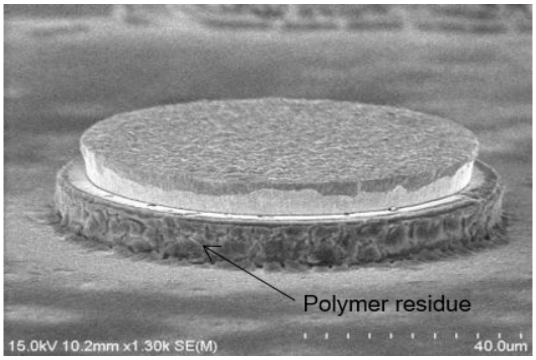

Fig. 3: SEM photograph of the side wall profile with Cl_2-based dry etching

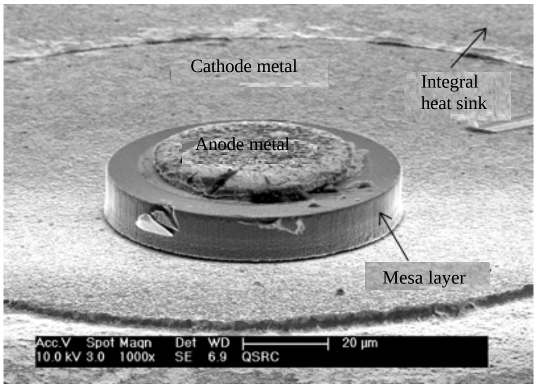

Fig. 4: SEM photograph after the combined mesa etching method using Cl_2-based dry etching and $FeCl_3$-based wet etching in due order

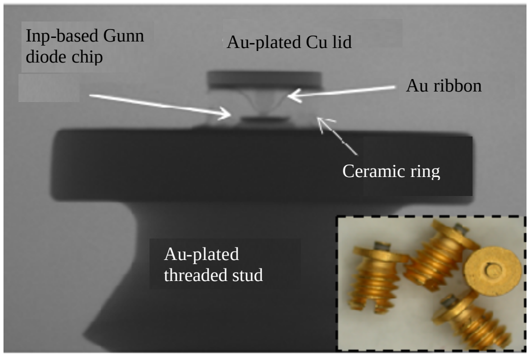

Fig. 5: X-ray image of the packaged InP-based Gunn diode (inset: optical image)

power of 2000 W and RF power of 200 W. Dry etching method also provides a good side wall profile that is a near vertical mesa walls, however it produces dirty polymer residue around side walls as shown in Fig. 3. These polymer scum on the fringe of mesa is due to high plasma density and long process time caused by a slow etch rate.

In order to overcome these drawbacks, mesa etching was performed by Cl_2-based dry etching and $FeCl_3$-based wet etching in due order. The side wall of mesa layer with the combined mesa etching method is vertical and clean as shown in Fig. 4. The combined mesa etching method caused an improved oscillation characteristics compared to those of only dry-etched or only wet-etched devices.

InP-based gunn diode package: Package elements for the InP-based Gunn diode consist of an Au-plated Cu stud, an Al_2O_3 ceramic ring an Au ribbon and an Au-plated Cu lid. The ceramic ring is mounted on the Au-plated Cu stud using AuSn solder. The fabricated InP-based Gunn diode chip was inserted in the ceramic ring and die-bonded on top of the Au-plated stud pedestal. The Au ribbon was used to make electrical contact between the InP-based Gunn diode chip and the Au-plated Cu lid. Then the upper side of the ceramic ring and the lid was joined using AgSn solder. The packaged InP-based Gunn diode is shown in Fig. 5.

RESULTS AND DISCUSSION

A 94 GHz waveguide oscillator for demonstration of the RF characteristics of the packaged InP-based Gunn diode was developed. It is a simple resonant disc circuit configuration as shown in Fig. 6. and 7 shows the photograph of the fabricated 94 GHz waveguide oscillator. The 94 GHz waveguide oscillator consists of a bias post and packaged InP-based Gunn diode in cavity for oscillation of 47 GHz. A fundamental signal oscillates at 47 GHz and a second harmonic signal of 94 GHz is output through an Iris filter and a WR-10. The bias post is used to supply dc bias to the packaged InP-based Gunn diode and has a low pass filter to prevent the oscillation power from leaking through the bias post. The bias post also has a resonator which control the frequency of oscillation. The back short position is used to optimize the output power.

An oscillation frequency and an output power of the fabricated waveguide oscillator were measured using an Agilent E4407B spectrum analyzer with an extended harmonic mixer and an Agilent E4419B EPM series power meter.

A typical set of performance curves for the fabricated waveguide oscillator is shown in Fig. 8 where an output power and an oscillation frequency are plotted against dc bias voltages. When the anode diameter of InP-based Gunn diode was 60 µm, typical values of oscillation frequency and output power were 94.25 GHz and 16.11 dBm with a dc-to-RF conversion efficiency of 1.6%, respectively, at 9.0 V of dc bias. The highest output power

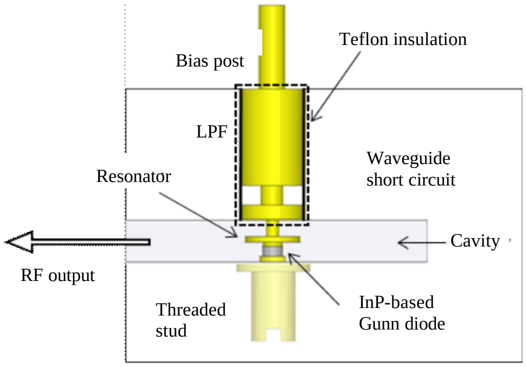

Fig. 6: Schematic diagram of the fabricated 94 GHz waveguide oscillator

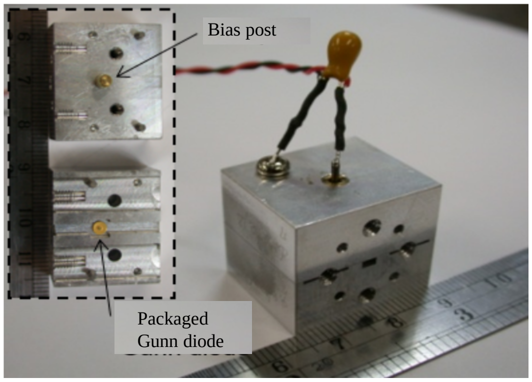

Fig. 7: Photograph of the fabricated 94 GHz waveguide oscillator

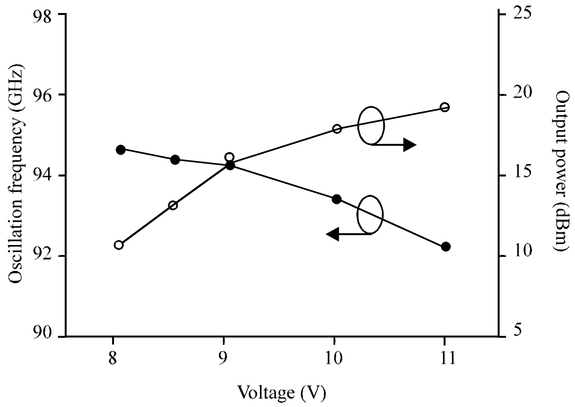

Fig. 8: Oscillation frequency and output power of the fabricated InP-based Gunn diode.

of 19.1 dBm was obtained with a dc-to-RF conversion efficiency of 2.5%, at 11 V of dc bias. The dc current during operation is about 250~300 mA.

Figure 9 shows the typical phase noise of the fabricated InP-based Gunn diode with the anode diameter of 60 μm under the bias condition of 9.0 V.

Table 1: Comparison of the results for the fabricated InP-based Gunn diode with other reported W-band Gunn diodes

Devicematerial	Oscillationfreq. (GHz)	Outputpower (dBm)	Ref.
InP	76.85	18.86	Franklin *et al.* (2000)
InP	93	14.77	Jones *et al.* (1999)
InP	94	20.86	Kurita *et al.* (1991)
InP	108	15.19	Kamoua *et al.* (1993)
GaAs	94	13.42	Amir *et al.* (2010)
GaAs	101.8	-10	Li *et al.* (2011)
GaAs	108	-43.5	Khalid *et al.* (2007)
InP	94.25	16.11	This research
	92.20	19.10	

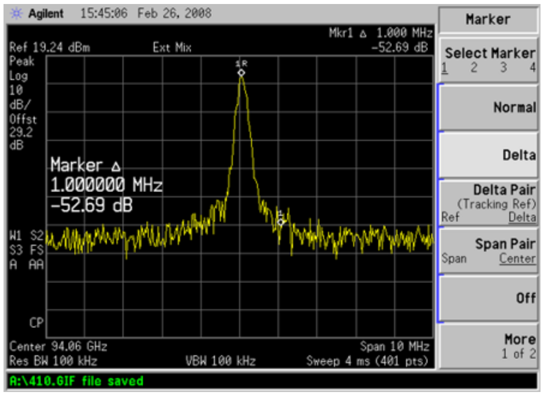

Fig. 9: Phase noise of the fabricated InP-based Gunn diode

The measured phase noise was <-102.9 dBc/Hz at 1 MHz offset. Resolution Bandwidth (RBW) was 10 KHz.

Table 1 shows comparison of the results for the fabricated InP-based Gunn diode with other reported W-band Gunn diodes. These values indicate that InP-based Gunn diode is superior to GaAs-based Gunn diode and the fabricated InP-based Gunn diode in this paper can be applied for many applications in W-band region such as millimeter-wave image sensor and FMCW radar. In addition, the fabricated waveguide oscillator in this paper used a second harmonic signal. However, if a waveguide oscillator for a fundamental mode oscillation is fabricated much higher output power will be obtained compared to that of a second harmonic mode oscillation.

CONCLUSION

In this study, we demonstrated the InP-based Gunn diode for W-band waveguide oscillator application. The fabricated InP-based Gunn diode has a SDL nn^+ structure for low operating currents and high efficiency. In order to improve oscillation characteristics, we optimized mesa etching process. The optimized mesa etching was performed by Cl_2-based dry etching and $FeCl_3$-based wet etching in due order. The 94 GHz waveguide oscillator for demonstration of the RF characteristics of the packaged InP-based Gunn diode was also developed. When the anode diameter of InP-based Gunn diode was 60 μm, typical values of oscillation frequency and output power were 94.25 GHz and 16.11 dBm with a dc-to-RF conversion efficiency of 1.6%, respectively, at dc bias of 9 V. The highest output power of 19.1 dBm was obtained with a dc-to-RF conversion efficiency of 2.5% at dc bias of 11 V. The measured phase noise was less than -102.9 dBc/Hz at 1 MHz offset with 10 KHz of resolution bandwidth. These values indicated that the fabricated InP-based Gunn diode in this paper can be applied for many applications in W-band region such as millimeter-wave image sensor and FMCW radar.

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