The design and manufacture of a notch structure for a planar InP Gunn diode*

Bai Yang(白 阳), Jia Rui(贾 锐)†, Wu De-Qi(武德起), Jin Zhi(金 智), and Liu Xin-Yu(刘新宇)

Institute of Microelectronics, Chinese Academy of Sciences, Beijing 100029, *China*

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A planar InP-based Gunn diode with a notch doping structure is designed and fabricated for integration into millimeter-wave and terahertz integrated circuits. We design two kinds of InP-based Gunn diodes. One has a fixed diameter of cathode area, but has variable spacing between anode and cathode; the other has fixed spacing, but a varying diameter. The threshold voltage and saturated current exhibit their strong dependences on the spacing (10 μm–20 μm) and diameter (40 μm–60 μm) of the InP Gunn diode. The threshold voltage is approximately 4.5 V and the saturated current is in a range of 293 mA–397 mA. In this work, the diameter of the diode and the space between anode and cathode are optimized. The devices are fabricated using a wet etching technique and show excellent performances. The results strongly suggest that low-cost and reliable InP planar Gunn diodes can be used as single chip terahertz sources.

Keywords: InP Gunn device, millimeter generation, planar Gunn diode

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1. Introduction

Gunn diodes have been commonly used as reliable solid-state frequency sources in many areas, such as imaging, material analysis, wideband wireless communications, and chemical or biological sensing, especially as important microwave and millimeter-wave signal sources converting direct current (DC) into radio frequency (RF) output power.[1–3] The Gunn oscillator meets some device requirements including small dimension and low phase noise.[4,5] GaAs is a suitable material for the generation of frequency up to 70 GHz and this frequency limitation can be extended by the extraction of higher harmonics, while InP Gunn diodes operate up to 110 GHz in fundamental mode. However, recent numerical studies show that the frequencies generated from diodes with a GaAs/AlGaAs structure could be expanded from 70 GHz to 75 GHz–110 GHz in second-harmonic-mode operation and those generated from the InP diodes could be expanded to 480 GHz in third-harmonic-mode operation.[6–8] Moreover, InP Gunn diodes demonstrated that they can bring out high RF output power levels compared with GaAs.[8–10] Khalid *et al*.[11] and Huang *et al*.[12] have realized planar Gunn diode structures fabricated with GaAs/AlGaAs material. Therefore, we show the experimental realization of an InP planar Gunn diode with an n–n+ structure, and study the current–voltage characteristics, with diameter and distance between anode and cathode for W-band Gunn diode changed.

In this paper we present a practical fabrication process for high-power microwave and millimeter-wave devices. The device has a notch structure, which is very efficient compared with graded and uniform doping devices, as domains will form very close to the cathode, which is indicated by the theoretical data of Monte Carlo simulations.[10] In this process, the heat sink layers are developed on both the substrate and the surface of device (see Fig. 1), without damaging the active layer and the buffer layer. We observe the nonlinear current–voltage curve and the negative different resistance region (NDR) characteristics corresponding to different dimensional Gunn diodes. The measured current–voltage curves show similar behaviors. What are performed on diodes are 40 μm–60 μm diameters and 10 μm–20 μm spacings. The characteristics of negative differential resistance and the asymmetry of the current–voltage curve corresponding to different dimension Gunn diodes will be discussed in detail later. The practical fabrication process for millimeter-wave applications is also presented in the paper.

2. Gunn diode structure

The epitaxial structure is grown by molecular beam epi-taxy (MBE) on a 370-μm thick, 2-inch-diameter semi-insulating (SI) InP substrate as shown in Fig. 1. The layers are, in growing sequence, a 100-nm InGaAs n^+ layer doped with over level of 2×10^{18} cm^{-3}, a 1.5-μm-thick n^+ InP buffer layer doped with Si at a level of 1×10^{18} cm^{-3}, and then a 1.8-μm-thick InP active layer doped with Si at 1.1×10^{16} cm^{-3}.[2,13,14] In the nn^+ structure is employed an alloyed metal current limiting contact, which forms a low barrier in the interface between the cathode contact and the active layer making the electrons depleted in the active region. As a result of the cathode depletion, these devices operate in a stable depletion layer

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†Corresponding author. E-mail: jiarui@ime.ac.cn

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(SDL) mode.[13–15] Thus, the nn$^+$ structure can effectively increase breakdown voltages up to 12 V.

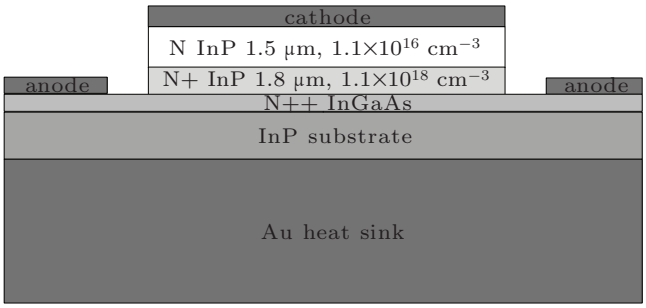


Fig. 1. Schematic diagram of the InP Gunn diode.

3. Fabrication of InP Gunn diodes

The Gunn diode is fabricated as shown in Fig. 2. Firstly, the circle metal pattern of cathode is formed by the photolithography technique using an AZ5214 photo-resist (PR). The contacts are then formed by evaporating Ge/Au/Ni/Au (500/900/300/1600 nm) on the low doping layer (active layer) using an electron beam evaporator. The PR is then stripped off and the device is annealed at 640 K for 60 s. Secondly, the cathode is protected by photolithography technique. After wet chemical etching in a solution of HCl-based etchant (37.5% HCl:85.5% H_3PO_4 = 1:4) for 5 min and 30 s, the mesa on the n$^+$ InGaAs contact layer is exposed. The etching rate is approximately 0.6 μm/min.

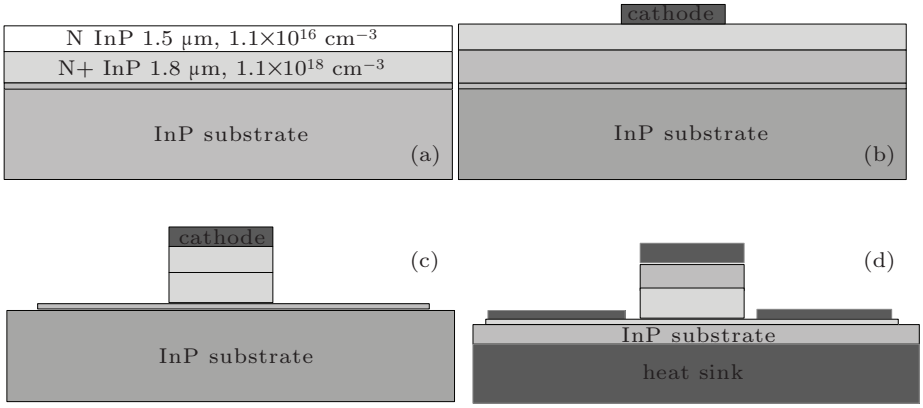


Fig. 2. Fabrication procedure of the InP Gunn diode. (a) MBE, (b) metallization of cathode, (c) MESA, and (d) metallization of anode and heat-sink (HS).

Thirdly, the circle metal pattern of cathode is formed by using 4400 PR to form the lift, followed by evaporating the same metals as cathode metal layers. Then it is annealed at 590 K for 60 s. Fourthly, the InP substrate is pasted on silicon wafer, and then lapped and polished on its back. Finally, a heat sink layer is formed using RF magnetron sputtering, followed by a 20-μm Au electroplating. In this way, the thermal conductivity of diamond is very high, so the device is mounted on a diamond for efficient heat dissipation.[8] The fabrication procedure of the InP Gunn diodes can be easily realised.

4. Device performance and analysis

4.1. Wet etching

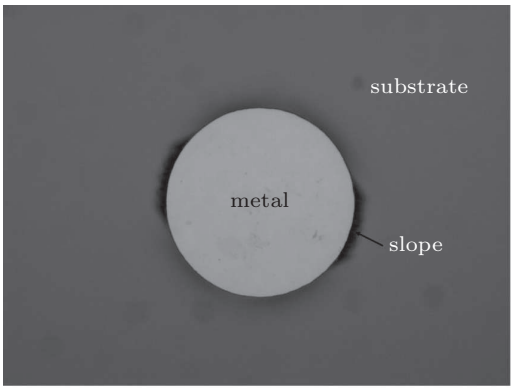
In order to achieve a smooth and uniform surface, a superior option is to carry out the etching in a HCl-based solution under an ultrasonic condition as shown in Fig. 3. In this way, the etching rate will keep uniform and the generation of bubbles will be reduced. The bubbles affect the etching process greatly, as they prevent the attachment of the etching solution to the InP layer. This effect results in an asymmetrical etching rate. Owing to anisotropic characteristics of the etchant, the etched profiles of the InP wafer with metal layers are shown by SEM in Fig. 3. The profile views displayed an excellent vertical side wall and a slope on (010). Mesa etching is properly delayed, which could wipe off the slope in the wet etching process as shown in Fig. 3(c). Moreover, the rate and the time of etch should be accurately controlled, as over etching on sidewall can be caused by the HCl-based solution. Therefore, it is better to observe the mesa height and side-wall profile repetitiously in order to achieve reliable etching performance.

In addition, we find that after 15-min etching in the solution, the mesa even becomes a square. This wet etching method is low-cost and is convenient to obtain an excellent mesa, compared with ICP and $FeCl_3$ light sensitive etchants.[13,15]

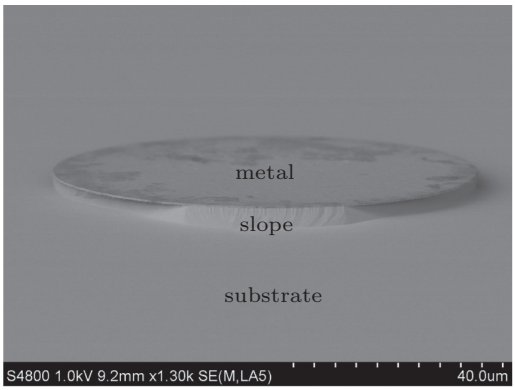
4.2. Heat dissipation

An important issue is how to address the inconsiderable influence of resistive heating in *I*–*V* measurement, since un-

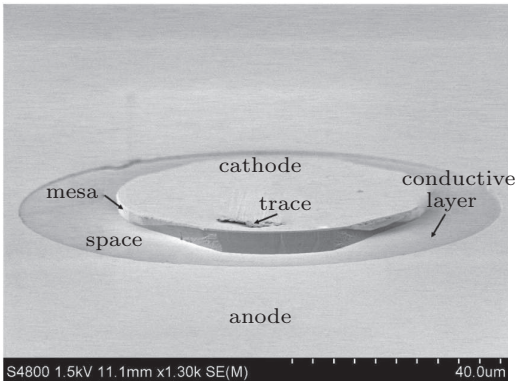
der normal operating conditions the diode temperature could easily reach 570 K. The heat is addressed by thinning and electroplating to make the diode work reliably under high temperature conditions. The thinning InP substrates and a heat sink of Au or diamond are typical methods to improve Gunn diode efficiency and output power.[8] Before thinning and Au plating, it is observed that current (DC) could destroy almost all diodes under 3 V by thermal reasons. While with thinning and a Au heat sink layer, the diode could work reliably in the high voltage area. In addition, this heat dissipation structure can cut down the cracks produced in lapping and polishing.



(a) Top side view



(b) Profile view wet etching InP substrate



(c) Gunn diode with proper etching time

Fig. 3. SEM images of the fabricated etching InP mesa. (a) A normal circular shape. (b) An excellent vertical side wall. (c) An excellent vertical side wall without a slope. The trace is caused by a probe in the measurement process. The diameter is 40 μm, and the spacing is 10 μm.

4.3. Measurement of the Gunn diode

Generally, a Gunn diode usually works in either accumulation layer mode or dipole mode. In accumulation layer mode, a density wave of electrons propagates along the active region of the device. While in dipole mode, a depletion layer precedes the density wave.[10] Electrons from the cathode must be accelerated for a certain distance to obtain sufficient energy and then are transferred to L-valleys from Γ-valleys, which narrows the active layer and forms the so-called dead zone. The dead zone due to the cathode region of the diode reduces the efficiency of the diode as the length that the domain can grow and transmit within is shorter. However, one method is to use a doping notch layer as shown in Fig. 1 to produce a high electric field in the notch. This stronger electric field will accelerate the electrons so as to allow them to gain enough energy to transfer to the satellite L-valley more quickly. Prior to RF measurements, each of the diodes is probed to evaluate their current–voltage (I–V) characteristics.[12] Therefore, the device is measured using both a pulsed I–V measurement system (here, the pulse width is 2 μs) and a combined DC voltage. Both can show the varying trend of I–V for the Gunn diode. However, the pulse test system can reduce the heat blight for the device, while the DC test system can demonstrate practical operating I–V characteristic. Hence, the device should be tested by using a pulse test system to find the break down voltage. And then it is tested by a DC test system.

The measured nonlinear characteristics of a Gunn diode with two different areas in the forward voltage are shown in Fig. 4. Forward voltage is applied to the anode (on the bottom of device). The electrons injected from the cathode flow to the anode through the transit region, so that current linearly increases under some voltage and the uptrend becomes a sharp decline with the voltage exceeding the threshold level. Therefore negative differential resistance can be observed, as the DC bias exceeds that level. In Fig. 4(a), the straight dashed line that indicates that Ohm's law is the fitted to a straight line compared with the I–V measurement curve. The varying trends of the I–V results are similar to those given by Huang *et al.*[12] and Khalid *et al.*,[11] however, their devices were fabricated in GaAs/AlGaAs. The voltage is above 3.7 V, where they began to separate from each other as labeled by the circles. However, the resistances of Gunn diodes are obviously higher at about 5 V than foregoing voltage according to Dunn and Kearney's theoretical data.[10] As the spacings are different, as shown in Fig. 4(b), the threshold voltages are approximately 7 V.

The increasing of the spacing will augment the threshold voltage, which will be added to series resistances, since electrons drift in the bottom n^+ InGaAs contact layer before entering into the metal conductor. The currents (DC) and threshold voltages of Gunn diodes are smaller than the ones under pulse stimulus. Their individual threshold voltages of 4.4, 4.6, and

4.6 V accord with those given by Dunn and Kearney[10] as shown in Fig. 5. Moreover it is demonstrated that the smaller size also corresponds to smaller current. These DC threshold voltages and saturated current densities are higher than those presented by Huang *et al.* (GaAs)[12] but lower than those provided by Khalid *et al.* (GaAs).[11] We find that the results

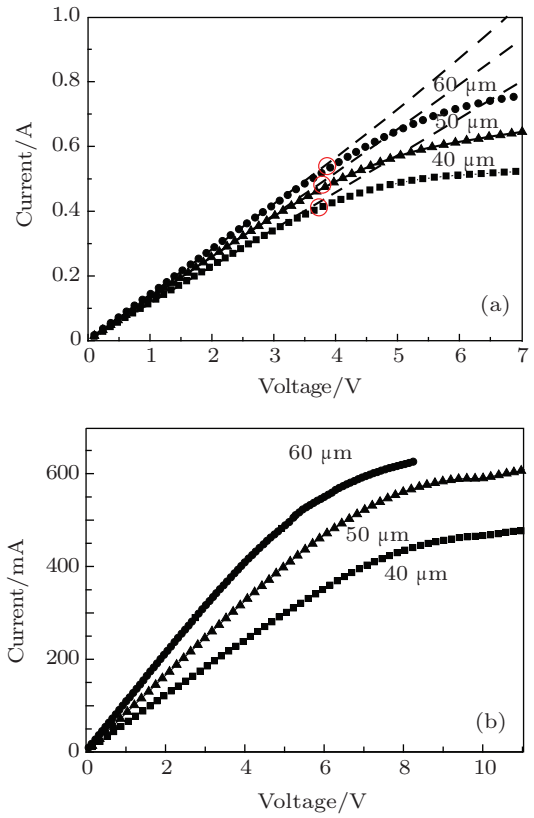


Fig. 4. (color online) Current–voltage characteristic curves of notch-doped profile Gunn devices with the same layer structure but different diameters (40, 50, and 60 μm) and different spacings (10 μm (a) and 20 μm (b)). The pulsed current–voltage curve is measured by cascade 12-K system.

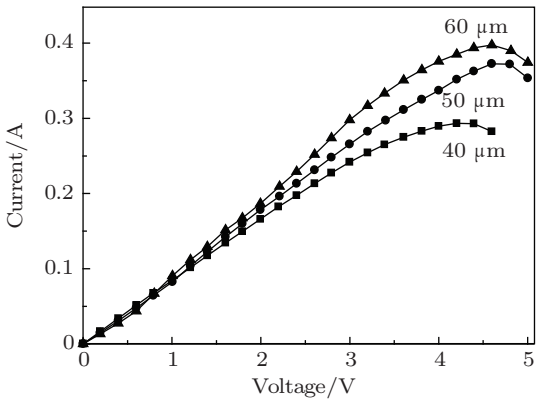


Fig. 5. Current–voltage characteristic curves of InP-based Gunn diode with the same designed spacing (20 μm) and three different diameters (40, 50, 60 μm).

are highly reproducible. As seen clearly in the figure, a typical *I–V* plot shows that there is a negative differential resistance region in the device. In addition, the device is more conductive under the condition of pulsed stimulus. These results are comparable to the theoretical data from Monte Carlo simulations and a prior study.[10]

5. Conclusions

We demonstrated a planar InP Gunn diode with a notch structure. It is proved that wet etching of InP Gunn diode mesas with a HCl-based solution can obtain excellent mesa profiles. In addition, the thinning of the wafer combined with a Au heat sink leads to perfect heat dissipation. Moreover, the threshold voltages and saturated currents for different sizes of Gunn diodes are measured. The smaller diameter of Gunn diode corresponds to a smaller saturated current, and the narrower spacing corresponds to lower threshold voltage and higher saturated current. InP material Gunn diodes will bring in a higher RF power and frequency output than GaAs. The new low-cost and high-reliable device will enable simpler monolithic microwave integrated circuits (MMICs) for a wide range of military and civilian applications.

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