Design and manufacture of planar GaAs Gunn diode for millimeter wave application*

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(Received 7 June 2010; revised manuscript received 8 July 2010)

GaAs-based planar Gunn diodes with AlGaAs hot electron injector have been successfully developed to be used as a local oscillator of 76 GHz in monolithic millimeter-wave integrated circuits. We designed two kinds of structure diode, one has a fixed distance between the anode and cathode, but has variational cathode area, the other has a fixed cathode area, but has different distances between two electrodes. The fabrication of Gunn diode is performed in accordance with the order of operations: cathode defining, mesa etching, anode defining, isolation, passivation, via hole and electroplating. A peak current density of 29.5 kA/cm^2 is obtained. And the characteristics of negative differential resistance and the asymmetry of the current–voltage curve due to the AlGaAs hot electron injector are discussed in detail. It is demonstrated that the smaller size of active area corresponds to the smaller current, and the shorter distance between anode and cathode also corresponds to the lower threshold voltage and higher peak current, and hot electron injector can effectively enhance the radio frequency conversion efficiency and output power.

Keywords: GaAs, planar Gunn diode, hot electron injector, millimeter generation

PACC: 7280E, 7340L, 7360L

1. Introduction

The GaAs Gunn diode is an active microwave element, which has low phase noise and exhibits self-sustained current oscillations when the applied DC voltage exceeds a threshold value. The Gunn diode is widely used as a local oscillator, which is largely based on high-cost cavity package due to its good thermal conductivity. Recently some groups made some attempts to fabricate planar Gunn diode such as field effect controlled transfer electron device (FECTED) and transverse active region Gunn diode based on electron beam lithography, and they also showed excellent RF performance comparable to that of conventional Gunn diodes in waveguide circuits.[1−3] Much attention also has been paid to such devices since they lend themselves to integration into millimeter-wave and terahertz integrated circuits. By combining air-bridge, electroplating and flip-chip bonding technologies,[4,5] the temperature stability of the Gunn diode has been greatly improved for application of millimeter wave oscillator. Meanwhile a graded gap $Al_xGa_{1-x}As$ barrier with hot electron injection effect has been adopted in the epitaxial layer in order to increase the intervalley electron transfer, and to expand the generation of frequencies from 70 GHz to 75–110 GHz in second-harmonic-mode operation, and reduce the dead-zone, which will improve noise performance, temperature stability and power conversion efficiency.[6] The planar Gunn is fabricated for monolithic millimeter-wave integrated circuits (MMIC) voltage controlled oscillators (VCO), which will represent a real alternative to MMIC oscillators based on the transistor,[7−9] and will open the door to Gunn diode applications in future.

2. Planar Gunn diode structure

The epitaxial structure studied was grown by molecular beam epitaxy (MBE) on a 2-inch, 350-μm thick, semi-insulating GaAs substrate, and a graded-gap injector at the cathode was employed in the material.[6,10,11] From bottom to top, the basic structure consists of a 0.7-μm-thick n^+ contact layer doped with Si (4.3×10^{18} cm^{-3}) , 1.6-μm-thick n^- GaAs active layer doped with Si at a level of 1.1×10^{16} cm^{-3}, followed by a 5-nm-thick n_s contact layer doped with

*Project supported by the Young Scientists Fund of the National Natural Science Foundation of China (Grant No. 60806024) and the Fundamental Research Funds for Central University of China (Grant No. XDJK2009C020).

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Si (1×10^{18} cm^{-3}), then an 50-nm-thick $Al_xGa_{1-x}As$ layer with a graded composition sandwiched between 10-nm GaAs space layer, and finally followed by a 0.5-μm-thick doped n^+ (4.3×10^{18} cm^{-3}) GaAs contact layer. In the planar Gunn structure, a 50-nm-thick graded-gap $Al_xGa_{1-x}As$ layer acts as hot electron injector, and highly doped n_s is used to avoid the formation of depletion region in active layer and weakening the effect of the hot electron injection. Two spacer layers placed on both sides of the AlGaAs layer are employed to prevent Si diffusion from the highly doped n^+ layer.[1] The $Al_xGa_{1-x}As$ graded-gap barrier is introduced to achieve as much as possible the electronic transfer between Γ-valley and L-valley and has been proved to be most successful.[12−14] The injector consists of two parts: a nominally undoped linearly-graded $Al_xGa_{1-x}As$ layer, where x increases linearly from 0 to 0.32 over 50 nm, and a thin highly doped n^+ GaAs layer, connecting the graded barrier to the active region of the Gunn diode. These parameters of linearly-graded $Al_xGa_{1-x}As$ layer ensure that the barrier height formed is equal to that of the Γ–L intervalley separation (0.31 eV).

3. Fabrication of GaAs Gunn diodes

The Gunn diode was fabricated as follows. First, the Ohmic metal pattern of cathode (first contact layer) was formed by an image reversal process using AZ5214 photoresist (PR) for the lift off process.[15] After the pattern lithography, to achieve Ohmic metallization we evaporated Ni/Ge/Au/Ge/Ni/Au (40/40/660/80/30/2200 Å, (1 Å=0.1 nm) using electron beam evaporator. Secondly, the first mesa etching was performed to expose the bottom n^+ GaAs contact layer by wet chemical etching with a solution of H_2SO_4:H_2O_2:H_2O=1:8:160 at an etching rate of 2000 Å/min. Then the fabrication of anode (second contact layer) was performed. The cathode and anode were then annealed at 375 °C for 60 second. Measurement of contact resistivity was carried out by the transmission line model (TLM) method with a typical result of 0.048 Ω·mm. The second mesa etching was followed to achieve electric isolation and diodes were passivated with 0.3-μm Si_3N_4. Then reactive ion etching was used to open windows over the metal contacts. Finally electroplating was executed to form bond-pads and the interconnection between the cathode and the expanded cathode bond-pads, and also was used to improve the heat dissipation of the Gunn diode. The plating processes are as follows. Ti/Au (300 Å/800 Å) was sputtered to form a seed layer for plating. The plating patterns were formed by positive lithography using 3.5-μm 9920 PR and a plating process was preformed to deposit a 3-μm-thick Au layer. After the plating process, the 9920 PR, part plating-Au and Ti/Au seed layer were sequentially stripped using acetone, an Au stripper and HF:H_2O=1:15, respectively.

Figure 1 shows a schematic diagram of the planar GaAs Gunn diode, and its corresponding scanning electron microscope (SEM) is presented in Fig. 2. The diode is in one port configuration, which is designed to on-wafer measure the S-parameter and DC characteristics. In the configuration, planar Gunn diodes with several different sizes have been used to study the relationship between the DC characteristics and the device structure of Gunn diode. The cathode has three variable rectangular area of 12×12, 20×30 and 30×40 μm^2, and the distance between the anode and cathode is fixed at 5 μm. Besides, the cathode has a rectangular area of 12×12 μm^2, the distance between anode and cathode varies from 5 μm to 15 μm with a step of 5 μm.

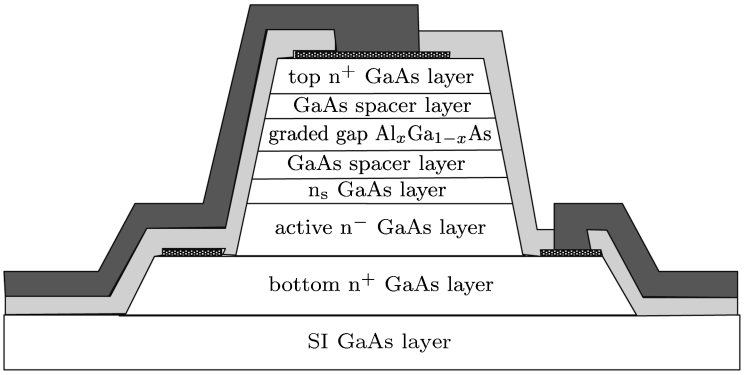


Fig. 1. Schematic diagram of the GaAs Gunn diode.

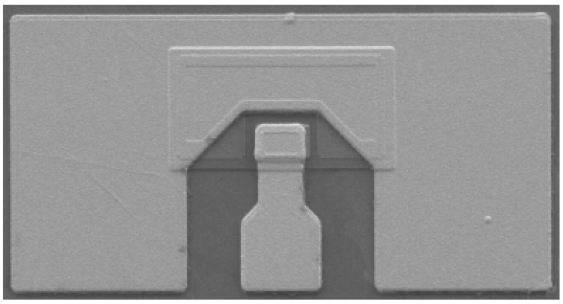


Fig. 2. The SEM of GaAs-based planar Gunn diode with one port.

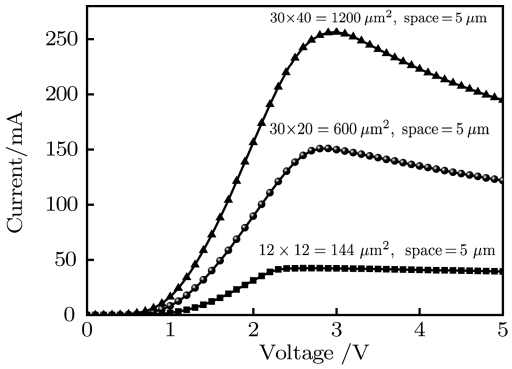


Fig. 3. The current–voltage characteristics of GaAs-based planar Gunn diode with fixed space between cathode and anode for three different areas: 144, 600, and 1200 μm^2.

4. Device performance and discussion

The measured DC characteristics of planar Gunn diode with three different areas in the forward voltage are shown in Fig. 3. Forward voltage means that a negative voltage is applied to the cathode on the top of device and reverses voltage means that a positive voltage does. In the forward voltage, the electron injected from the cathode flows to the anode through the transit region. When the DC bias exceeds the threshold level, negative differential resistance (NDR) is observed. Figure 3 shows that the current decreases with increasing applied voltage due to the formation of NDR region. The corresponding current decreases when the voltage is between the threshold voltage and the peak voltage. The threshold voltages $V_{\rm th}$ defining the onset of the NDR are approximately 2.8, 2.9, and 3.0 V for Gunn with areas of 144, 600, and 1200 μm^2, respectively. The corresponding peak current densities are 29.5, 25.3, and 21.3 kA/cm^2, respectively. These threshold voltages and peak current densities are higher than those by Mi–Ra, but lower than those by Simone.[2,13] The threshold currents of these Gunn diodes are made less than 500 mA to ensure a reliable device operation and to facilitate the on-wafer 8510 measurement of DC characteristics. The diode operating currents is designed between 40–300 mA. This is especially true for monolithic millimeter-wave integrated circuits where a smaller diode area is desirable because of temperature stability at high current density. Moreover it is demonstrated that the smaller size also corresponds to the smaller current.

In addition, the measured current–voltage characteristics of 12×12-μm^2 planar Gunn diode with three different spacings between cathode and anode (5, 10, and 15 μm) were shown in Fig. 4. It can be noted that there is an NDR region in the device when the DC biased voltage exceeds their individual threshold voltage of 2.7, 2.9 and 3.0 V. The device with space of 5 μm presents maximum current because of the shortest distance, which can reduce the series resistance, since electron has to drift in the bottom n$^+$ GaAs contact layer before entering the metal conductor.

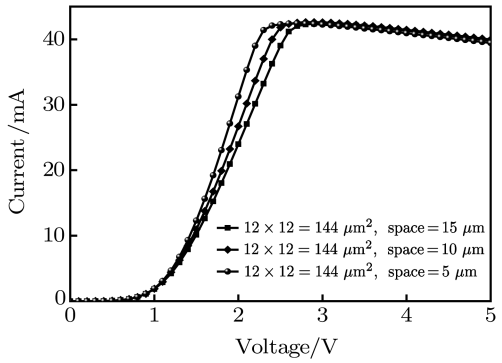


Fig. 4. Current–voltage characteristics of 12×12 μm^2 planar Gunn diode for three different spaces between the cathode and anode: 5 μm, 10 μm, and 15 μm.

The Gunn diode with graded-gap injector presents an asymmetric I–V curve shown in Fig. 5, which was entirely different from symmetric one of traditional Gunn diode with relatively low doped active region sandwiched between high doped n$^+$ layers. In the reverse voltage, electrons are injected into active region of the diode through the graded gap cathode and enhance the occupation of the L-valley, where they have high effective mass and low mobility. In the forward voltage, electrons directly enter the active region from the anode and the hot electron injector

acts as a series resistor. Therefore no enhanced L-valley occupation can be obtained from the Γ-valley, where they have low effective mass and high mobility. In the reverse voltage, higher L-valley occupation means a lower peak current because of lower drift velocity in L-valley. In contrary, higher Γ-valley occupation in the forward voltage leads to much higher peak current because of relatively higher drift velocity in Γ-valley. The performance above has been demonstrated in Fig. 5, where the ratio between the peak current maxima in the reverse direction and that in the forward one is 0.64 and can be used to measure the effectiveness of the injector.

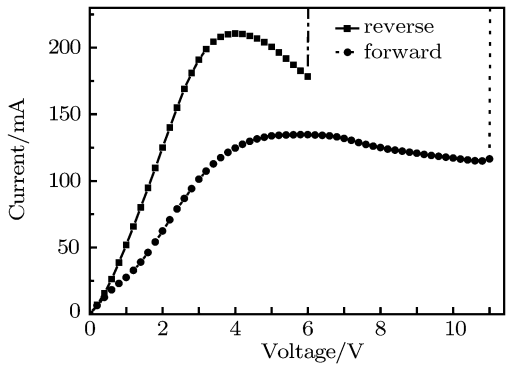


Fig. 5. The I–V characteristics of Gunn diode in the forward and the reverse directions. Gunn diode parameters: area is 30×40 μm^2, active region length is 1.6 μm, space between the anode and cathode is 5 μm.

The effect of hot electron injection near the cathode is employed in order to improve the DC-to-RF conversion efficiency and temperature stability. The injector effect is obtained by introducing a 50-nm-thick graded-gap $Al_xGa_{1-x}As$ layer between the cathode contact layer and the active layer. Generally, electrons from the cathode must be accelerated for some distances to obtain sufficient energy and then is transferred to L-valleys from Γ-valleys, which narrows active layer and forms the so-called dead-zone. The dead-zone introduces an undesirable positive serial resistance reducing the RF power and DC-to-RF conversion efficiency. However, these problems can be solved by introducing a hot electron injector in the cathode above the Gunn diode active region. The main task of the $Al_xGa_{1-x}As$ graded barrier is to transfer electrons as many as possible from the Γ-valley to the L-valley at the beginning of the device-active region. The hot electron injection effect can be investigated by measuring the peak current ratio between the forward voltage and the reverse voltage, which has been presented in Fig. 5, and S-parameter, which will be further measured in future.

5. Conclusion

Planar GaAs-based Gunn diode with graded gap AlGaAs layer is designed and fabricated for MMIC Gunn oscillator at 76-GHz, and the DC performances such as those of the negative resistance were discussed for different device structures and their corresponding microwave measurements will be performed further. We gained good hot electron injection effect due to graded-gap AlGaAs layer, which has been confirmed by a remarkable asymmetric I–V curve. It is demonstrated that the smaller size of anode corresponds to the smaller current, and the shorter distance between anode and cathode also corresponds to the lower threshold voltage and higher peak current. The planar Gunn device will enable simpler MMIC for a wide range of military and civilian applications.

Acknowledgement

The authors would like to thank the Institute of Physics, the Chinese Academy of Sciences for providing the GaAs-based Gunn diode material grown by MBE, and thanks Li Yan-Kui for the help of the electronic measurement.

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