High performance oscillator with 2-mW output power at 300 GHz*

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(Received 20 August 2013; revised manuscript received 19 November 2013; published online 25 March 2014)

Material structures and device structures of a 100-GHz InP based transferred-electron device are designed in this paper. In order to successfully fabricate the Gunn devices operating at 100 GHz, the InP substrate was entirely removed by mechanical thinning and wet etching. The Gunn device was connected to a tripler link and a high RF (radio frequency) output with power of 2 mW working at 300 GHz was obtained, which is high enough for applications in current military electronic systems.

Keywords: InP, transferred electron devices, terahertz wave, negative differential resistance

PACS: 72.80.Ey, 73.40.Lg, 73.61.Ey **DOI:** 10.1088/1674-1056/23/5/057204

1. Introduction

Transferred electron devices have been widely used for high-frequency sources because of advantages such as their small size, low cost, etc. since the first Gunn device was developed in 1963. Gunn oscillations, regimed in micro/nano-scale devices, can reach in the terahertz range,[1] which can be used in a wide range of applications including imaging, communication, medical, military electronic systems, etc.[2–4] Although a lot of effort has been made to improve the upper frequency limit and RF (radio frequency) power level of three-terminal devices, transferred electron devices based on negative differential resistance effects still play an irreplaceable role in many system applications with high RF power levels. Thanks to their excellent properties, including low noise andwide work frequency in medium-power oscillators,[5,6] they have found wide use as the local oscillators and drivers for multiplier or amplifier chains in many system applications.

At present, the application of terahertz waves is being extended from 300 GHz to 500 GHz to meet the requirement for applications in environmental monitoring and astronomical research.[7] Although GaAs-based transferred electron devices can offer 100-mW power in 6-mm band, the output power of these kinds of devices is dramatically reduced in the W-band, especially at frequency above 94 GHz. Therefore, devices with a higher output power working at the frequency above 100 GHz based on other materials such as InP are required in order to solve today's increasingly crowded band resources.[8–10] It has been reported that InP-based transferred electron device oscillators have yielded a 480-GHz frequency output by the third harmonic extraction.[8,11,12] However, the output power is only a few tens of microwatts, which is too low to be easily used. In this paper, InP material was selected to fabricate transferred electron devices. In order to fabricate the high frequency devices, the InP substrate was entirely removed and excellent omhic contacts on the devices were made.[13,14] By connecting the Gunn devices to a tripler link, an excellent 300-GHz RF source with power of 2 mW was obtained.

2. Design and fabrication of 100-GHz transferred electron devices

As a body-effect device, the final electrical properties of the transferred electron devices are determined by the length L of the active layer and the saturation velocity v_s. The domain transit time can be given by $T \approx L/v_s$. The time of the initial growth of a small fluctuation t_{gr} is determined by the differential dielectric relaxation time τ_{md}

$$t_{gr} \approx 3|\tau_{md}| = \frac{3\varepsilon}{q|\mu_d|N_0}, \tag{1}$$

where ε is dielectric constant, μ_d is carrier mobility, and the N_0 is doping concentration. The formation time of a stable propagating domain t_{gr} should be considerably smaller than the transit time

$$\frac{3\varepsilon}{q|\mu_d|N_0} < \frac{L}{v_s}, \tag{2}$$

which leads to the famous Kroemer criterion

$$N_0L > (N_0L)_1 = \frac{3\varepsilon v_s}{q|\mu_d|}, \tag{3}$$

For InP, $\varepsilon = 1.11 \times 10^{-10}$ F/m, $\mu_d = 0.32$ m^2·V^{-1}·s^{-1}, $v_s \approx 1$–2×10^5 m/s, so $L = 1$–2 μm and $N_0L < 10^{12}$ cm^{-2}. Therefore, when the N_0L product is close to 10^{12} cm^{-2} or above, stable propagating domains will be formed in the active layer. Thus, the length of the active layer of 100-GHz InP

*Project supported by the Main Direction Program of Knowledge Innovation of the Chinese Academy of Sciences (Grant No. 2A2011YYYJ-1123).
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transferred electronic devices was designed to be 1.1 μm in this experiment.[15] The material structure for fabricating 100-GHz InP-based transferred electron devices was designed as shown in Fig. 1.

To ensure an ideal output performance for electron devices, a good ohmic contact is required.[16,17] However, it is not easy to form an ohmic contact on InP because InP material is difficult to be highly-doped. Therefore, in our experiment, a highly doped InGaAs layer on N^+-InP layer was used to facilitate the formation of good ohmic contacts. It was confirmed by experiments that specific contact resistance as low as 3.2×10^{-7} Ω·cm^2 can be achieved by inserting a layer of highly-doped InGaAs. In general, the conversion efficiency of 100-GHz Gunn source working in high field is only 2% resulting in devices been heated up to 470 K. Therefore, effective heat dissipation is a prerequisite for ensuring that Gunn devices operate properly.[3] In this work, the integral heat sink (IHS) process is selected to dissipate heat in our design.[18,19] In addition, InP substrate needs to be removed to minimize the series resistance to ensure that the devices work at a frequency of 100 GHz. The material structure and the deposition parameters are given in Table 1 and Fig. 1.

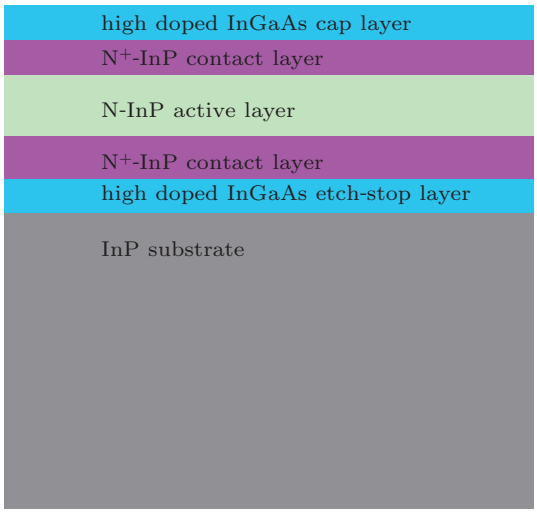


Fig. 1. (color online) Material structures of InP Gunn diodes.

Table 1. Deposition parameters.

Name	Material	Thickness/nm	Dopant	Doping/cm^{-3}	Comment
Cap layer	$In_{0.53}Ga_{0.47}As$	60	Si	2×10^{19}	
Contact layer1	InP	500		1.2×10^{19}	lattice matched composition
Drift zone	InP	1100		$(1–3)\times10^{16}$	#
Contact layer2	InP	500		1.2×10^{19}	lattice matched composition
Etch stop	$In_{0.53}Ga_{0.47}As$	200	Si	2×10^{19}	
Buffer	InP	50	ud	–	
	InP substrate			N^+-type	

The InP-based transferred electron devices were fabricated in the following steps. The 100-micron-wide trenches were first etched on the sample surface to release stress between the semiconductor and the heat sink, which can reduce the formation of cracks in the epi-layers in the next processing. Cracks were caused by the difference in the thermal expansion coefficients between the semiconductor and the heat sink. These trenches were etched down to InP substrate to facilitate checking the degree of mechanical thinning. An n-ohmic contact (Ni/Ge/Au/Ge/Ni/Au) was then evaporated over the whole surface and 20-μm gold was plated to form the integral heat sink.

After forming the heat sink, the sample was attached to a quartz tray and the substrate was removed by a finest grinding step and wet etching. The InGaAs layer can be either used as a contact layer or etched away. Figure 2 shows the optical images before and after removing the InGaAs etch-stop layer. It can be clearly seen that there are no cracks in it.

In the next step, standard lithography techniques were used to define circular diodes with a size of 35 μm in diameter, and then they were metalized to form n-ohmic contacts. A 3-μm Au was plated on the top of the evaporated layers in order to solve the bonding problems. Then the semiconductor material between the circular contacts was etched away to form the mesa. The sample was subsequently annealed by rapid thermal processing. The cross section of the final structure is shown in Fig. 3.

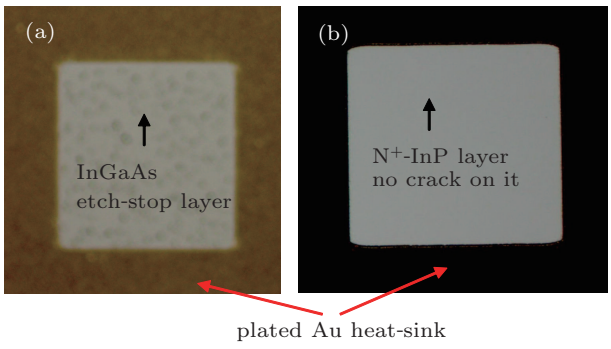


Fig. 2. (color online) Results after grinding (a) and wet etching (b).

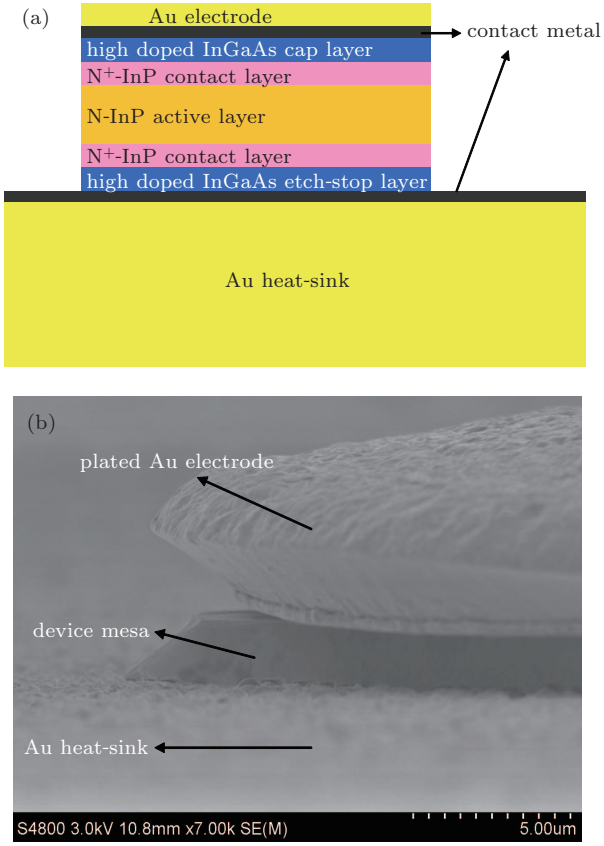


Fig. 3. (color online) (a) Schematic diagram of the mesa. (b) SEM image of the diode after mesa etching.

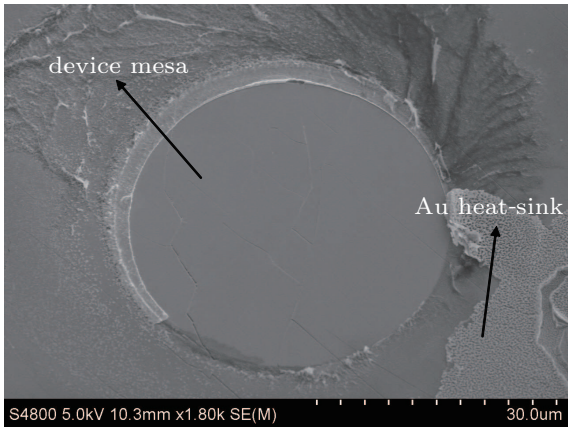


Fig. 4. Mesa etched by inductively coupled plasma.

Note that the mesa can also be formed using dry etching technology, however, it is not easy to control the etch rate. The mesa etched by inductively coupled plasma is shown in Fig. 4.

Next, the diodes were mounted on copper heat sinks. The 20-μm gold threads were thermo-compression bonded to a bond diode and to the ceramics standoffs. The encapsulated cylindrical diode was placed in a 100-GHz waveguide cavity as shown in Fig. 5.

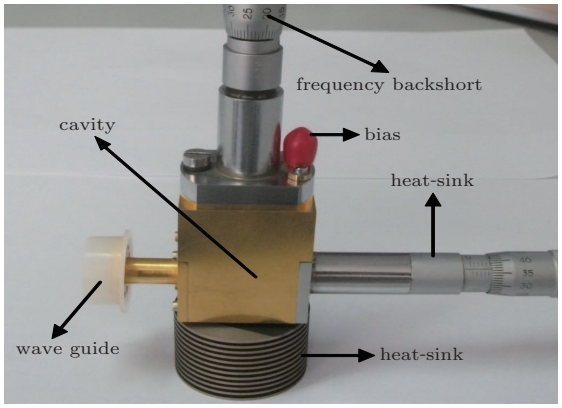


Fig. 5. (color online) The 100-GHz waveguide.

3. Results

The measured nonlinear characteristics of a Gunn diode under the forward voltage are shown in Fig. 6. A highly reproducible result can be gained as seen in the figure. There is a negative differential resistance region when the applied voltage is over 2 V. These results are comparable to the theoretical results calculated by Dunn *et al.* using the Monte–Carlo

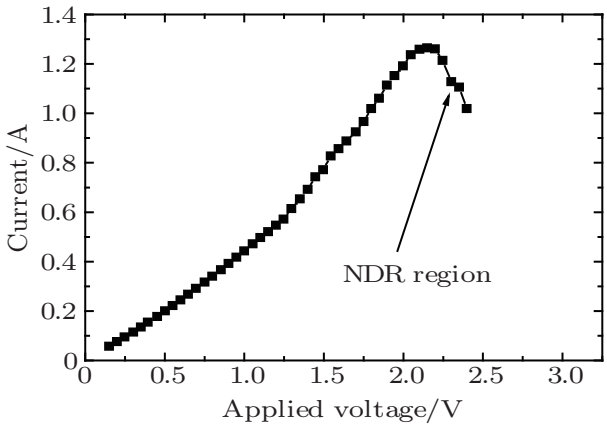


Fig. 6. NDR curve of InP TEDs.

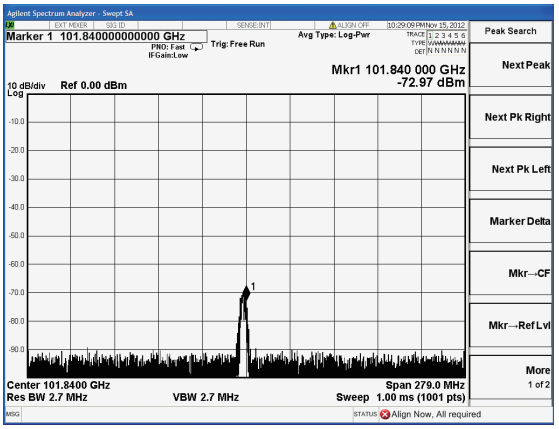


Fig. 7. (color online) Frequency output of InP TEDs at 2.5 V.

method.[10]

The results showed in Fig. 6 suggest that RF output should be generated when the applied voltage is over 2 V. The signal at 101 GHz was observed as showed in Fig. 7 when the device was forward biased at 2.5 V, at which the device worked in the negative resistance regime. This indicates that the fabrication process for millimeter-wave devices has met its practical demands.

Finally, the 100-GHz Gunn device was connected to a tripler link in the way shown in Fig. 8 to obtain a high power output. A 300-GHz RF output for the Gunn device under 3.5 V forward bias was obtained as shown in Fig. 9. The output power of 2 mW was confirmed by a power-meter. In this way, a milliwatt-level output was obtained using Gunn sources, which is high enough for applications in medical, imaging, communication and military electronic systems.

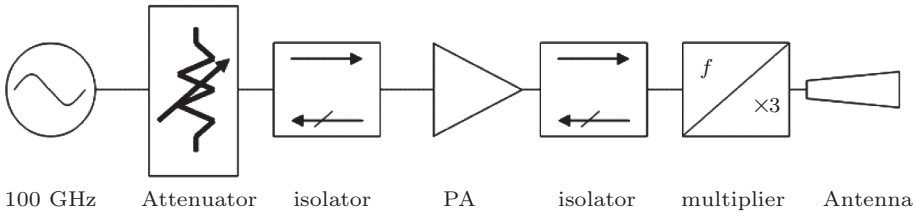


Fig. 8. The tripler link.

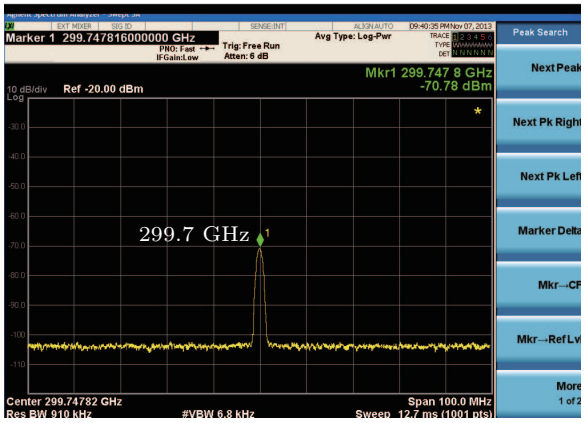


Fig. 9. (color online) Frequency output of InP TEDs at 3.5 V, after linked to a tripler link.

4. Conclusion

After we solved issues such as the fragility of InP material processing, ohmic contacts, heat dissipation, etc., the 100-GHz InP-based Gunn source was eventually fabricated. A 2-mW RF signal at 300 GHz was gained by connecting the 100-GHz Gunn source to a tripler link, which basically solved the problem that the output power of terahertz Gunn source is low and difficult to use.

Acknowledgments

The authors would like to thank Wang Su-Qin and Wang Xian-Tai for their insightful discussion and Li Yan-Kui and Ning Xiao-Xi for their technical support.

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