An InP-based heterodimensional Schottky diode for terahertz detection*

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Abstract: We present an InP-based heterodimensional Schottky diode (HDSD), which has so far never been reported in the literature. Compared to a GaAs-based HDSD, the InP-based HDSD is expected to have better high frequency performance and operational conditions resulting from its higher mobility and concentration of 2D electron gas (2DEG) as well as its smaller Schottky barrier height. The cutoff frequency of the InP-based HDSD obtained by the AC measurement is more than 500 GHz, which shows its potential application in terahertz detection.

Key words: Schottky barrier diode; heterodimensional Schottky diode; InP; terahertz detection
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1. Introduction

Terahertz (THz) radiation, which lies in the frequency gap between microwave and infrared radiation, is a significant research topic in recent years because of its promising applications in communication[1], security[2], biological and medical sciences[3], earth and space sciences[4] and basic science[5] etc. Just like terahertz sources, terahertz detection is an essential part of terahertz technology.

A conventional Schottky barrier diode (SBD)[6], which has a low forward drop and a very fast switching action, is a practical detector which operates at room temperature whereas other detectors such as the hot electron bolometer (HEB)[7] and superconductor–insulator–superconductor (SIS) mixer receiver[8] operate at cryogenic temperatures. The detection mechanism using SBD is the rectification of the radiation induced AC signal due to the barrier nonlinearity[9]. More details regarding the common experimental arrangement can be obtained in Ref. [10]. However, the high frequency performance of a conventional SBD for terahertz detection is still limited by the RC product (with reference to Eq. (1)), although its operation at over several terahertz has been reported[11]. C_j and R_s in Eq. (1) represent the junction capacitance and series resistance respectively.

$$f_c = \frac{1}{2\pi R_s C_j}. \tag{1}$$

A heterodimensional Schottky diode (HDSD) is a unique kind of SBD with a 3D metal–2D semiconductor Schottky junction, and has been proposed for a long time. Shur *et al.*[12−16] had designed and fabricated an HDSD in the early 1990s and put forward some modeling theories. Since the Schottky junction is a lateral Schottky junction (LSJ), the depletion region of the HDSD expands in the direction of the channel and thus the effective channel length is decreased and can even be modulated by an applied voltage. The series resistance can be described by the expression in Eq. (2), where μ_n and n are the mobility and density of electrons in 2D electron gas (2DEG), L is the channel length and L_d is the length of the depletion region, S is the lateral Schottky junction area and R_c is the ohmic contact resistance. So the high $n\mu_n$ product of the 2DEG will lead to a small series resistance R_s. On the other hand, the small lateral Schottky junction area S will lead to a small junction capacitance C_j. Both the small series resistance and the small junction capacitance make the cutoff frequency higher than conventional Schottky diode (with reference to Eq. (1)). Thereby it is feasible to apply it in terahertz detection.

$$R_s = \frac{1}{qn\mu_n}\frac{L - L_d}{S} + R_c. \tag{2}$$

Additionally, other similar heterodimensional devices, such as heterodimensional FET, heterodimensional FET with split drain[17] and Schottky grated resonant tunneling transistor (SGRTT)[18] were also reported.

Most of the material systems referred to above are based on GaAs while the device presented in this paper is based on InP. There are two potential advantages of an InP-based HDSD in comparison with a GaAs-based HDSD. Firstly, the 2D electron gas (2DEG) in an InP heterostructure has a higher mobility and density so that the series resistance is smaller (with reference to Eq. (2)). This will lead to a higher cutoff frequency. Secondly, since InP has a smaller Schottky barrier height, the operational conditions are expected to be around the zero bias voltage[19], which will lead to advantages such as a simple system and low power consumption[20]. Up to now, an InP-based HDSD has never been reported in the literature.

2. Device design and fabrication

The layer sequence and structure of the InP HDSD is illustrated in Fig. 1. A high cutoff frequency f_c is the most critical

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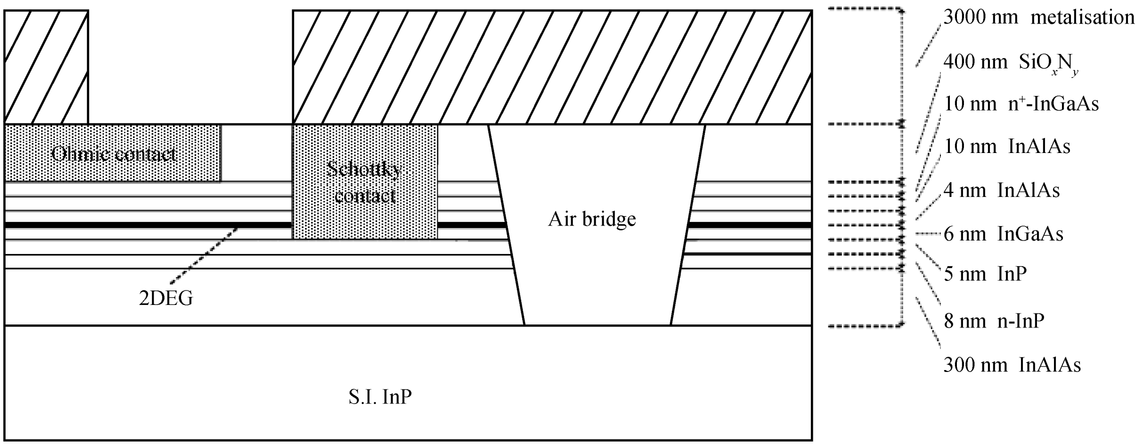

Fig. 1. Layer sequence and structure of the InP HDSD.

parameter of the InP HDSD for the purpose of terahertz detection. So, according to Eqs. (1) and (2), the device design such as the material design, device structure and process technology are all optimized to obtain the highest cutoff frequency f_c, i.e. the smallest $R_s j_c$ product within our fabrication ability.

First of all, the InAlAs/InGaAs/InP heterostructure should be designed to have a high mobility and density of electrons in a 2DEG. The heterostructure was grown by molecular beam epitaxy on a 2-inch semi-insulating InP substrate. The electron sheet charge density of 2DEG was 3.2×10^{12} cm^{-2} and the mobility was measured to be 8560 cm^2/(V·s) at room temperature.

As to the device structure, the channel length L should be short to reduce the series resistance R_s (with reference to Eq. (2)), but it is limited by our fabrication ability. As a result of this tradeoff, the designed channel length L is 2 μm. Considering that the air bridge can reduce the parasitic capacitance[21], the anode air bridge should be introduced in the device structure as illustrated in Fig. 1. In addition, the anode and cathode pad were designed to be separated from each other with a long distance for reducing both the potential parasitic capacitance and the risk of forming a short circuit. Furthermore, for the measurement of the AC characteristics of this device, a coplanar waveguide (CPW) configure was designed for on-wafer test.

A 400-nm-thick SiO_xN_y was deposited by plasma enhanced chemical vapor deposition (PECVD) as a protection layer. The ohmic contact was then defined and the SiO_xN_y layer was etched by reactive ion etching. Ohmic contact metals, GeAuNiAu, were deposited onto the n^+ layer by electron-beam evaporation followed by rapid annealing. After the Schottky contact was defined, the SiO_xN_y layer and the InGaAs/InAlAs layer were etched in turn to form a trench through the 2DEG layer. The lateral Schottky contact was formed by sputtering the Ti/Pt/Au layer onto the surface of the trench. The wafer surface was sputter coated with 10 nm/150 nm Ti/Au as a seed layer. The contact pad and finger were formed by electroplating a 3-μm-thick gold layer and removing the undesired Ti/Au layer by wet etching. Finally the SiO_xN_y layer, InGaAs/InAlAs layer, InP layer and InAlAs layer were removed one by one to isolate individual devices on the same wafer and form the air bridge simultaneously.

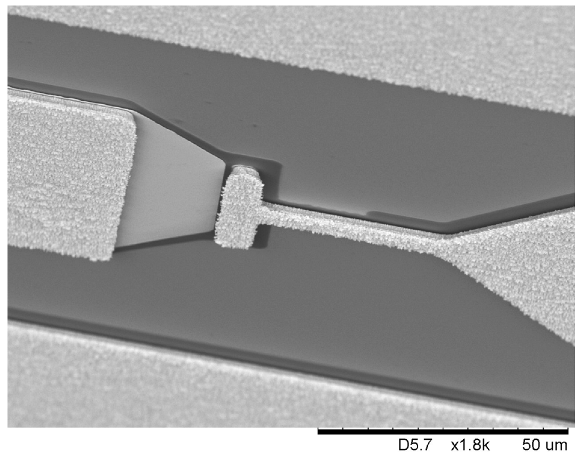

Fig. 2. SEM image of InP HDSD.

3. Results and discussion

The SEM image of the device fabricated is shown in Fig. 2. The channel length is measured to be 1.6 μm, a little shorter than the designed 2 μm due to the effect of lateral etching. Meanwhile the air bridge under the finger is easily identified in Fig. 2.

The DC characteristics of the device were measured by an Agilent 4256A. The I–V characteristic shown in Fig. 3 is consistent with the typical I–V curve of a Schottky diode. The breakdown voltage is more than 5 V and the current density at 9 V is 120 kA/cm^2. The high forward voltage drop is attributed to imperfect ohmic contact resistance due to the fact that the doping level of the cap layer is 5×10^{18} cm^{-3} and the layer thickness is only 10 nm. Furthermore, it has also been reported that by alloying over a long time rather than the rapid annealing we used here can form a better ohmic contact[22].

Then an AC measurement of up to 40 GHz was carried out by vector network analyzer (VNA) after calibrating the VNA by the standard short-open-load-through method. Considering that the typical small signal equivalent circuit comprises junction capacitance, series resistance and other parasitic components[23], we used a specific small signal equivalent circuit with the topology shown in Fig. 4 to simulate the AC characteris-

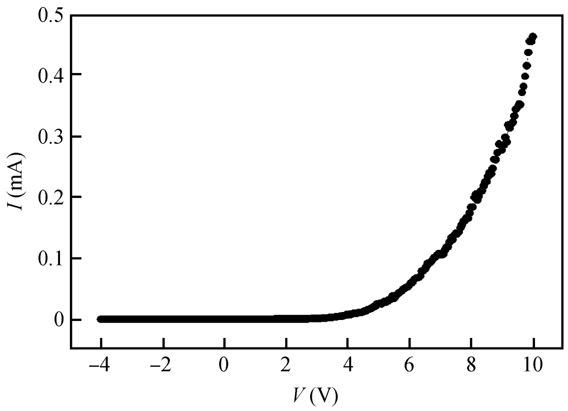

Fig. 3. I–V characteristics of InP HDSD.

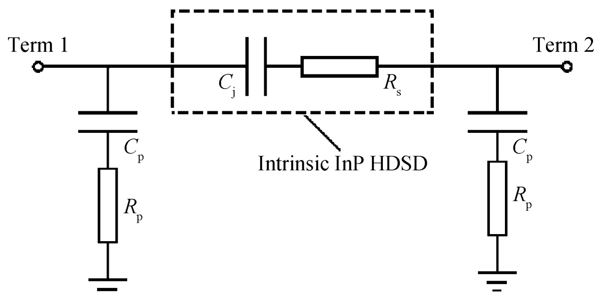

Fig. 4. Small signal equivalent circuit of the on-wafer InP HDSD.

tic of the on-wafer device. Wherein, C_j and R_s represent the junction capacitance and series resistance of the intrinsic InP HDSD respectively, while C_p and R_p are parasitic components caused by the on-wafer CPW configure.

After simple optimization, the simulated S parameter (the dashed line) matched well with the measured S parameter (the solid line) as illustrated in Figs. 5 and 6. The optimized C_j is 12.6 fF while the optimized R_s is 22.2 Ω. So we can calculate the cutoff frequency of the intrinsic InP HDBD like this,

$$f_{\text{cutoff}} = \frac{1}{2\pi R_s C_j} = 569 \text{ GHz}. \quad (3)$$

According to Shur *et al.*[12, 14], HDSD sometimes exhibits excess series resistance which is attributed to insufficient metal plating in the anode trench and high ohmic contact resistance. The same phenomenon also exists in the device we present here. According to Eq. (2), the imperfect ohmic contact resistance R_c demonstrated above causes excess series resistance. Meanwhile the insufficient metal plating can also be the cause of excess series resistance since the 2DEG is several nanometers thin. To improve the high frequency performance of InP-based HDSD, we could take several measurements. We could enhance the doping level as well as the thickness of the cap layer, and use slow annealing instead of rapid annealing to reduce the ohmic contact resistance. Optimized fabrication steps such as better metal plating in the trench will also be helpful. Moreover, shunt conduction paths between the two pads should be eliminated to control the parasitic capacitance. Since the cutoff frequency of improved GaAs-based HDSD is reported to be about 800 GHz at room temperature[12, 14], improved InP-based HDSD can be expected to have a cutoff frequency well into the terahertz frequency range. So the InP-based HDSD we present here has a potential application in terahertz detection.

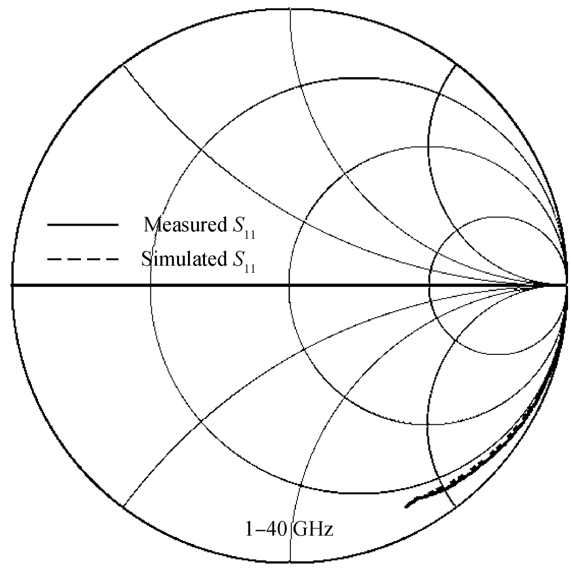

Fig. 5. Measured S_{11} with simulated S_{11} of the on-wafer InP HDSD.

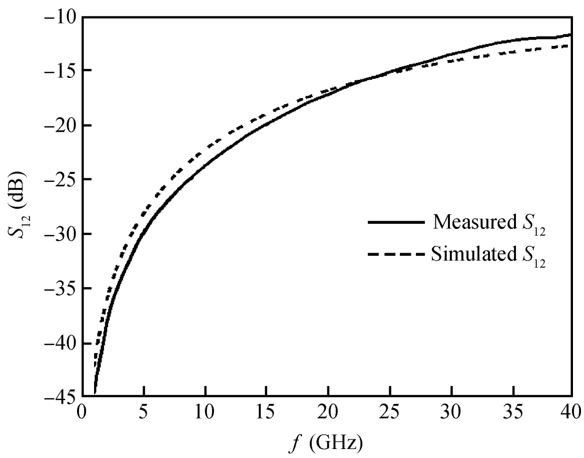

Fig. 6. Measured S_{12} with simulated S_{12} of the on-wafer InP HDSD.

4. Conclusion

In summary, HDSD based on an InAlAs/InGaAs/InP heterostructure has been designed and fabricated. The channel length is 1.6 μm and the SEM illustrates a clear air bridge under the finger. The measured I–V curve behaves as expected while the cutoff frequency obtained by the AC measurement is more than 500 GHz. All these features show its potential application in terahertz detection. Some measures to improve the performance of this device have also been suggested.

References

[1] Hirata A, Kosugi T, Takahashi H, et al. 120-GHz-band millimeter-wave photonic wireless link for 10-Gb/s data transmission. IEEE Trans Microw Theory Tech, 2006, 54(5): 1937

[2] Kawase K, Ogawa Y, Watanabe Y, et al. Non-destructive tera-

hertz imaging of illicit drugs using spectral fingerprints. Opt Express, 2003, 11: 2549
[3] Woodward R, Cole B, Wallace V, et al. Terahertz pulse imaging in reflection geometry of human skin cancer and skin tissue. Phys Med Biol, 2002, 47: 3853
[4] Waters J, Froidevaux L, Harwood R, et al. The earth observing system microwave limb sounder (EOS MLS) on the aura satellite. IEEE Trans Geosci Remote Sensing, 2006, 44: 1075
[5] Padilla W, Taylor A, Highstrete C, et al. Dynamical electric and magnetic metamaterial response at terahertz frequencies. Phys Rev Lett, 2006, 96: 107401
[6] Zhang Haiyan, Ye Zhizhen, Huang Jingyun, et al. Fabrication of Schottky barrier diodes of high frequency based on thin silicon epilayer. Chinese Journal of Semiconductors, 2003, 24(6): 622 (in Chinese)
[7] Wei J, Olaya D, Karasik B, et al. Ultrasensitive hot-electron nanobolometers for terahertz astrophysics. Nature Nanotechnology, 2008, 3: 496
[8] Kikuchi K, Yamada T, Kohjiro S. Development of superconductor–insulator–superconductor (SIS) terahertz receiver with mechanical and thermal vibration-reduced cryocooler. IEEE Trans Appl Superconductivity, 2011, 21: 649
[9] Bozhkov V. Semiconductor detectors, mixers, and frequency multipliers for the terahertz band. Radiophysics and Quantum Electronics, 2003, 46: 631
[10] Titz R, Roser H, Schwaab G. Investigation of GaAs Schottky barrier diodes in the THz range. International Journal of Infrared and Millimeter Waves, 1990, 11: 809
[11] Yasui T, Nishimura A, Suzuki T, et al. Detection system operating at up to 7 THz using quasioptics and Schottky barrier diodes. Rev Sci Instrum, 2006, 77: 066102
[12] Peatman W, Crowe T, Shur M. Design and fabrication of heterostructure varactor diodes for millimeter and submillimeter wave multiplier applications. High Speed Semiconductor Devices and Circuits, 1991: 49
[13] Gelmont B, Shur M, Moglestue C. Theory of junction between two-dimensional electron gas and p-type semiconductor. IEEE Electron Devices, 1992, 39(5): 1216
[14] Peatman W, Crowe T, Shur M. A novel Schottky/2-DEG diode for millimeter- and submillimeter-wave multiplier applications. IEEE Electron Device Lett, 1992, 13(1): 11
[15] Gelmont B, Peatman W, Shur M. Heterodimensional Schottky metal-two -dimensional electron gas interfaces. J Vac Technol B, 1993, 11(4): 1670
[16] Ytterdal T, Shur M, Hurt M, et al. Enhancement of Schottky barrier height in heterodimensional metal–semiconductor contacts. Appl Phys Lett, 1997, 70(4): 441
[17] Cheng T, Mathewson A, Kenndy M, et al. Heterodimensional FET with split drain. IEEE Electron Device Lett, 2004, 25(11):737
[18] Shur M, Peatman W, Park H, et al. Novel heterodimensional diodes and transistors. Solid-State Electron, 1995, 38(9): 1727
[19] Shousha A. Optimum barrier height for Schottky-barrier detectors. J Phys D, 1982, 15: 669
[20] Ito H, Nakajima F, Ohno T, et al. InP-based planar-antenna-integrated Schottky-barrier diode for millimeter- and submillimeter-wave detection. Jpn J Appl Phys, 2008, 47(8): 6256
[21] Yu Jinyong, Liu Xinyu, Su Shubing, et al. InP/InGaAs heterojunction bipolar transistor with base μ-bridge and emitter airbridge. Chinese Journal of Semiconductors, 2007, 28(2): 154
[22] Liu Liang, Yin Junjian, Li Xiao, et al. Ohmic contact for InP-based HEMTs. Chinese Journal of Semiconductors, 2007, 27(11): 1970 (in Chinese)
[23] Garfield D, Mattauch R, Bishop W. Design, fabrication, and testing of a novel planar Schottky barrier diode for millimeter and submillimeter wavelengths. IEEE Southeastcon, 1988: 154