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InGaAs/InAlAs HEMT Terahertz Detector Integrated with Patch Antenna

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Abstract

An InGaAs/InAlAs HEMT terahertz (THz) detector integrated with slot-coupled patch antennas, which does not require a Si lens, was fabricated and characterized. A maximum transconductance of 0.77 S/mm and sub-threshold slope (*S.S.*) of 100 mV/dec were obtained with 60-nm gate HEMT, and a voltage responsivity of 400 V/W was achieved at 600 GHz.

1. Introduction

The terahertz (THz) frequency range located between the lightwave and millimeter wave has been receiving considerable attention because of its many possible applications, such as imaging, spectroscopy, and high-capacity wireless communications [1]. Compact, high responsivity, and low noise detectors are key components for various applications of the THz waves. THz detectors using field effect transistors (FETs) have been studied [2-5]. We proposed and fabricated a THz detector using an InGaAs composite-channel HEMT [6]. A high current responsivity R_i of 13 A/W was achieved using a 45-nm gate-length HEMT with maximum transconductance $g_{m.max}$ of 2.35 S/mm [7]. However, a millimeter-scale hemispherical Si lens is usually required beneath the HEMT detector to detect THz signal.

In this study, we propose and fabricate an InGaAs/InAlAs HEMT THz detector integrated with slot-coupled patch antennas, which does not require a Si lens. We obtained a $g_{m.max}$ of 0.77 S/mm and *S.S.* of 100 mV/dec with 60-nm gate length, and a voltage responsivity of 400 V/W at 600 GHz.

2. Experiments

The schematic device structure of our HEMT THz detector integrated with patch antenna is shown in Fig. 1. An InP-based InAlAs/InGaAs composite-channel HEMT with two-finger T-shaped gates was integrated at the center of a slot antenna. The slot and patch antennas are inductively coupled [8], and irradiated THz signal is entered to gate electrodes. HEMT has diode-like characteristics in the I_d–V_g characteristics, and an irradiated THz wave can be detected by rectification.

The epitaxial layer structure was grown by molecular beam epitaxy on semi-insulating (100) InP substrates. From bottom to top, the layers consist of a 200-nm InAlAs buffer, a 10-nm InGaAs composite-channel, a 3-nm InAlAs spacer, a Si δ-doping of 5×10^{12} cm^{-2}, a 3-nm InAlAs barrier, a 6-nm InP etching-stopper, a 10-nm layer of n$^+$-InAlAs (3×10^{19} cm^{-3}), and a 15 nm n$^+$-InGaAs contact layer (5×10^{19} cm^{-3}). The 2-DEG mobility and density were 12300 cm/Vs and ~3×10^{12} cm^{-2}, respectively, from Hall measurements at room temperature.

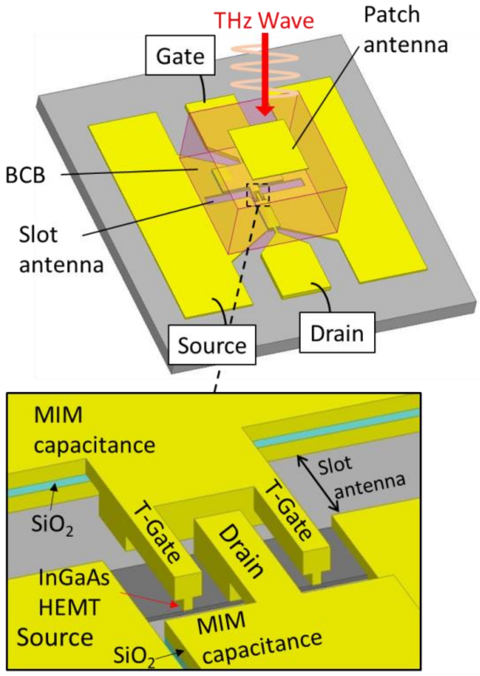

Fig. 1 Schematic of the HEMT THz detector structure integrated with patch antenna.

A tri-layer resist was used to form the T-shaped gate and a Pt-buried gate process was used to reduce the short channel effect. The fabrication process is briefly described as follows. First, the device was isolated by wet chemical etching ($H_2SO_4/H_2O_2/H_2O$) using a ma-N resist (Micro Resist Technology) mask. The source, drain, and antenna electrodes (Ti/Pd/Au) were formed by the standard lift-off process using a polymethyl methacrylate (PMMA) resist. The slot antenna length was 50 µm. The HEMT surface was covered with a SiO_2 film as an etching mask for the formation of the gate recess structure. A tri-layer resist (ZEP/PMGI/ZEP) was coated onto the SiO_2 film. The top and bottom ZEP layers were separately exposed using 50-keV electron beam irradiation. The gate pattern was replicated on the SiO_2 film using CF_4 inductively coupled plasma reactive-ion etching (ICP-RIE), and the gate recess structure was formed by wet chemical etching. T-shaped gate electrodes (Pt/Ti/Pt/Au) were deposited. The gate length was 60 nm. Finally, a low-dielectric benzocyclobutene (BCB) layer is stacked on the device, and a square patch antenna is formed on the BCB layer. The slot resonator is positioned directly underneath the center of the patch antenna.

The slot and patch antennas are inductively coupled, and an antenna main robe is obtained in the upward direction due to the patch antenna. In addition, to achieve resonance with the oscillation frequency, we designed the side of the patch antenna perpendicular to the slot to be approximately $\lambda/(2n_{\mathrm{BCB}})$ long, where λ is the wavelength of the oscillation frequency in free space and n_{BCB} is the refractive index of the BCB layer. We used an antenna length of 140 μm for resonance at 0.6 THz. The magnetic field parallel to the slot is generated by a slot resonator, and is coupled with the patch antenna. The BCB layer thickness is designed to be 10.5 μm, which is much thinner than the oscillation wavelength.

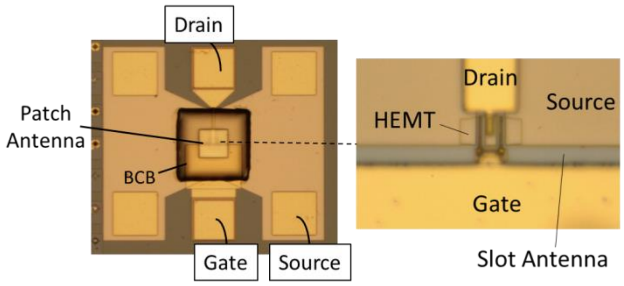

Fig. 2 Micro-photographs of fabricated HEMT detector.

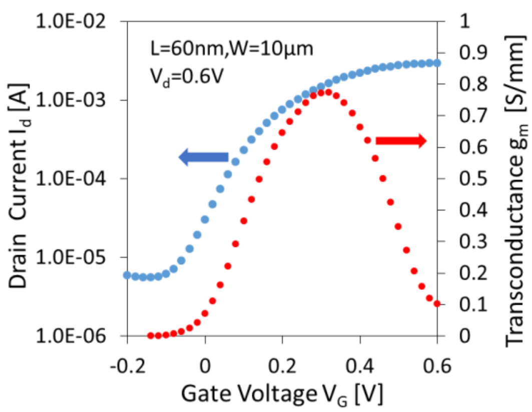

Fig. 3 I_{d}-V_{g} and transconductance characteristics.

The measured I_{d}-V_{g} and transconductace characteristics were shown in Fig. 3. The drain bias V_{d} was 0.6 V. We obtained a $g_{\mathrm{m.max}}$ of 0.77 S/mm. The measured *S.S.* value was 100 mV/dec. The voltage responsivity, measured as a function of frequency, is shown in Fig. 4. The peak responsivity is 400 V/W at 600 GHz, corresponding to patch antenna resonance.

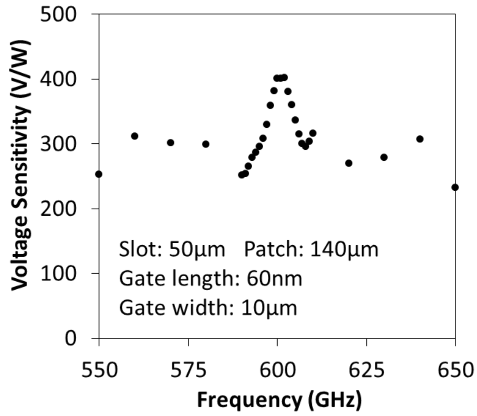

Fig. 4 Frequency dependence of voltage responsivity. The peak responsivity of 400 V/W is obtained at resonance frequency of patch antenna (600 GHz).

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