Plasmonic Terahertz Wave Detector Based on Silicon Field-Effect Transistors with Asymmetric Source and Drain Structures

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Since terahertz (THz) wave detection mechanism by using oscillations of channel plasma waves based on a field-effect transistor (FET) structure was proposed by Dyakonov and Shur [1], FETs with 2-dimensional electron gas (2DEG) in the channel have been intensively investigated as the promising plasmonic detectors of THz radiations. In this letter, we report the experimental demonstrations of the enhanced responsivity in Si metal-oxide-semiconductor (MOS) FET-based plasmonic THz detector [2, 3] with asymmetric source and drain region considering the device width variations.

The devices with L_g= 2 μm, and t_{ox}= 50 nm were fabricated on the 1 × 10^{15} cm^{-3} p-doped <100> Si wafer. The threshold voltage (V_{th}) extracted from the transfer characteristics at low drain bias was within the range of V_{th}= 0.2~0.6 V for all devices (see Fig. 1). Figure 2 shows the measurement setup with lock-in amplifier system for the responsivity of the fabricated plasmonic THz detector. The sub-THz radiation with frequency f= 0.2 THz was generated by a gyrotron source in higher order mode resonator, which enables real-time detection with the continuous-wave (CW) method since it is stable in sub-THz frequency regime [4]. Figure 3 shows the image of the detector contact pads on the wafer sample with bonding wires. It should be noted that these bonding wires also can act as antennas by exposing directly to THz wave since the wire length is longer than the half of the wavelength ($\lambda/2= f/2c$= 0.75 mm at f= 0.2 THz) [3, 5]. Figure 4 presents the micrograph image (top view) of the fabricated Si FET with asymmetric source and drain structure. Asymmetric structure condition is determined by split of the source width W_S as 2 μm, 10 μm, 15 μm, and 20 μm with the fixed drain width W_D= 20 μm. The corresponding asymmetry ratio η_a (= W_D/W_S.) would be 10, 2, 4/3, and 1 respectively.

As shown in Fig. 5, the peak values of the measured Δu to 0.2 THz radiation near threshold increase as the electric current of the gyrotron source grows from 70 to 100 mA. It should be noted that these response signals totally result from the gyrotron THz source since there is no response signal when the current is 0 A. The emission power at the end of waveguide has been estimated as 10 W by using the calorimeter when the electric current in our gyrotron source is 80 mA (default) and the actual power to be delivered onto the detector may be reduced by considering the device dimension and diffraction limit. In Fig. 6, we obtained the reproducible photoresponse for various detectors (T1~T4) with different asymmetry ratio (η_a= 10 for T1 and T2, η_a= 4/3 for T3 and T4) and more enhanced responsivity for the detectors with larger asymmetry ratio (T1, T2 with η_a= 10). The responsivity in this plot of Fig. 6 has been normalized by the maximum value (T1, T2) with arbitrary unit in order to confirm the relative photoresponse results for the different asymmetry ratio. In our proposed asymmetric structure, these asymmetric boundary conditions internally arise by the difference of the gate overlap capacitances between source and drain and thus, the responsivity R_V starts to appear and increases as the structural asymmetry between source and drain area under the gate increases. To find the maximum R_V at their own antenna coupling effects for each asymmetry ratio η_a, the detector sample holder is rotated from 0° to 360° step-wise with 30° (12 steps) in the transverse plane of the polarized THz wave propagation, because the orientation of the bonding wires has significant effect on the response signal to the polarized THz radiation [5]. Figure 7 shows the normalized experimental data R_V versus detector sample rotation angle and indicates that the peak R_V occurs at the different rotation angle (210° for T1 with η_a= 10 and 0° for T3 with η_a= 4/3) that is aligned with gate bonding wires to the polarized radiation. By considering these orientation effects with the bonding wires on the photoresponse, we obtained the more enhanced R_V about 5 times as η_a increases from 4/3 to 10, while the response signal in the symmetric detector (square) is negligibly small as shown in Fig. 8. At the same initial angle of 0°, however, it was 2.4 times of R_V ratio between η_a= 4/3 and 10 (see Fig. 6).

In conclusion, we have experimentally demonstrated that the plasmonic THz detector based on Si FETs with asymmetric source and drain structures can enhance the responsivity at room temperature. These results can provide the possibility of the performance enhancement focusing on the asymmetric design of source and drain structure under the gate in field-effect devices without additional considerations of external antenna and amplifier integration.

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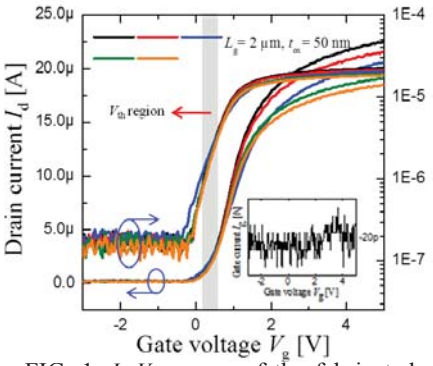

FIG. 1. I_d-V_g curves of the fabricated Si-FETs. The threshold voltage V_{th} extracted from these DC curves at V_d= 1 V. Inset shows the negligible gate current for all gate voltages.

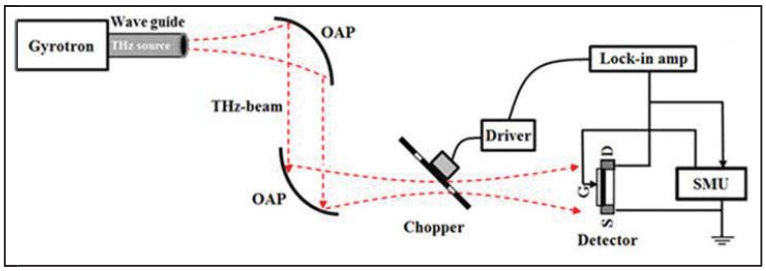

FIG. 2. Schematic of the experimental setup for plasmonic THz detector using 0.2 THz gyrotron source

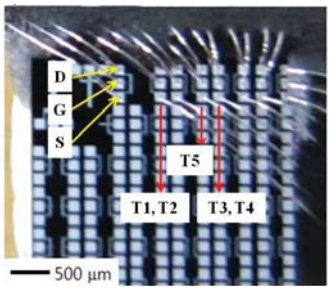

FIG. 3. Photo image of the detector sample with bonding wires on the sample board. (η_a= 10 for T1 and T2, η_a= 4/3 for T3 and T4, η_a= 2 for T5).

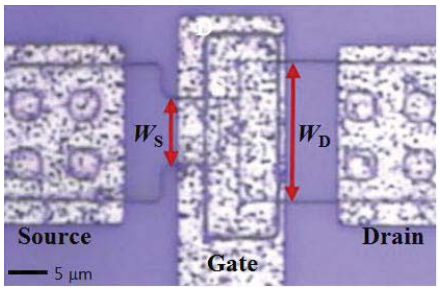

FIG. 4. Micrograph (top view) of the fabricated Si FET with asymmetric source and drain. Drain width W_D= 20 µm and source width W_S = 2, 10, 15, and 20 µm with corresponding asymmetry ratio η_a = W_D /W_S is 10 (T1, T2), 2 (T5), 4/3 (T3, T4) and 1 (symmetric), respectively.

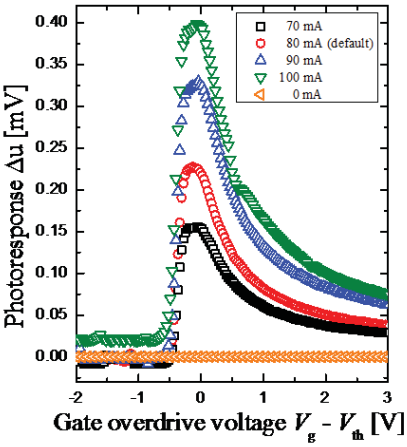

FIG. 5. Experimental results of the Si FET response signal to 0.2 THz radiation. Photoresponse Δu as a function of the gate overdrive voltage $V_g - V_{th}$ for different emission power by varying the current in gyrotron source.

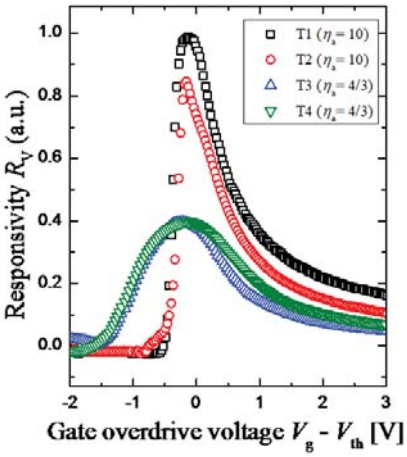

FIG. 6. Responsivity R_v as a function of $V_g - V_{th}$ for various Si FETs (T1, T2, T3, T4) with different values of the asymmetry ratio η_a = 10, 4/3.

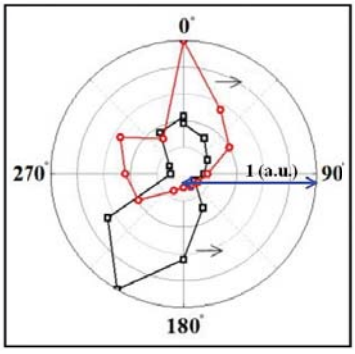

FIG. 7. The normalized ampli- tude of the response signal versus sample rotation angle. The detector sample holder is rotated from 0 to 360° step-wise with 30° in the transverse plane of THz ray.

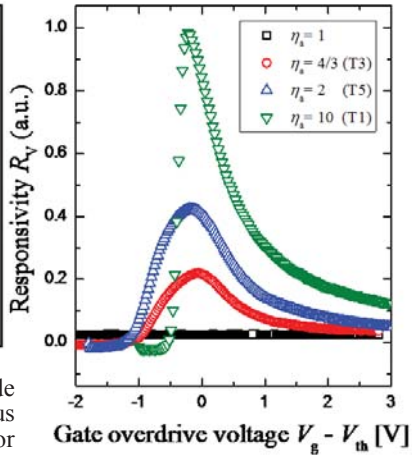

FIG. 8. Responsivity R_v as a function of $V_g - V_{th}$ for the different asymmetry ratio η_a are 10 (T1), 2 (T5), 4/3 (T3), and 1 (symmetric).