Terahertz detection by GaN/AlGaN transistors

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Detection of subterahertz and terahertz radiation by high electron mobility GaN/AlGaN transistors in the 0.2–2.5 THz frequency range (much higher than the cutoff frequency of the transistors) is reported. Experiments were performed in the temperature range 4–300 K. For the lowest temperatures, a resonant response was observed. The resonances were interpreted as plasma wave excitations in gated two-dimensional electron gas. Non-resonant detection was observed at temperatures above 100 K. Estimates for noise equivalent power show that these transistors can be used as efficient detectors of terahertz radiation at cryogenic and room temperatures.

More than ten years ago, Dyakonov and Shur proposed using submicron field effect transistors (FETs) as sources and detectors of terahertz electromagnetic radiation [1, 2]. Since that time both detection and generation in the sub-THz and THz frequency range have been experimentally demonstrated using compound semiconductor and silicon transistors [3–10]. For detection, the regimes of the resonant and non-resonant operation are distinguished. When $\omega\tau \ll 1$, the FET operates in the non-resonant regime, where ω is the radian frequency and τ the plasmon decay time; the transistor response to the electromagnetic radiation is a decreasing function of the gate voltage. When $\omega\tau \gg 1$, the transistor has a resonant response at resonant plasma frequencies $\omega_n = \omega_o(1 + 2N)$, where $N = 0, 1, 2, \ldots$, $\omega_0 = (\pi/2L_g)\sqrt{(e^2 n_s/Cm)}$ is the fundamental radian plasma frequency, L_g is the gate length, n_s is the channel concentration, C is the gate capacitance per unit area, m is the effective mass, and e is the electron charge. The decay time is equal to or shorter than the scattering rate. It might be affected by the ballistic transport [11], the viscosity of the electron fluid owing to electron-electron collisions [1], and by a possible effect of oblique plasma modes [12].

Since the channel concentration is a function of the gate voltage, the FET in the resonant mode of operation is a tunable detector of THz radiation. In spite of the experimental demonstration of resonant sub-THz detection by GaAs-based transistors (see [7] and references therein) and THz detection by InGaAs-based transistors [13], this mode of operation remains a challenge to achieve. Since GaN/AlGaN heterostructure FETs (HFETs) have extremely high electron concentration in the channel (exceeding 10^{13}cm^{-2}), these transistors with gate length $L_g < 200$ nm have a high value of ω_o, which makes them good candidates for resonant THz detectors.

In this Letter, we demonstrate the resonant and non-resonant plasma detection of THz radiation by GaN/AlGaN HFETs at cryogenic and room temperatures. Such detectors could also operate at high temperature and in a harsh environment because of the nitride materials' properties. The HFETs with gate length of 150 nm and total gate width of 150 µm were fabricated by IEMN-DHS UMR CNRS. The 300 nm nucleation layer grown on 4H-SiC was followed by $Al_{0.25}Ga_{0.75}N$ layers of 2750 nm buffer, 5 nm spacer, 5 nm Si-doped supply layer, and 10 nm barrier layer. The structures were capped with a 2 nm undoped GaN layer. The distance between the source and drain was 3 µm, and the Schottky barrier gate was located at 1 µm distance from the source. The HFETs with a gate length of 250 nm were fabricated by Sensor Electronic Technology, Inc. The epitaxial structures were grown by metal organic chemical vapour deposition (MOCVD) on a sapphire substrate. They consisted of a 100 nm-thick AlN buffer layer, a 2.0 µm-thick undoped GaN layer, followed by a $Al_{0.3}Ga_{0.7}N$ barrier layer, which was doped with silicon to approximately 2×10^{18} cm^{-3}. The samples were mounted on a quartz plate to avoid parasitic interference and reflections. They were than placed into a closed-cycle helium cryostat behind the THz radiation transparent polyethylene window. The response to THz radiation at varying gate voltages was measured as a DC voltage on the open drain with the source grounded. The THz and sub-THz radiation was generated by a CO_2 pumped methanol vapour laser (0.76 THz, 2.5 THz), a Gunn diode (0.2 THz) source, and back-wave oscillators (BWO) operating in the 500–700 GHz and 200–400 GHz ranges. The incident radiation of 3–10 mW (depending on the frequency and the source) was focused into a spot of about 1–10 mm diameter, which was larger than or comparable to the overall size of the transistors with the contact pads.

Fig. 1 shows the transistor response, ΔV, to the 0.76 and 2.5 THz radiation against gate voltage. Above 70 K, only the non-resonant detection was observed. At lower temperatures, the resonant detection revealed itself as a shoulder or maximum (shown by arrows in Figs. 1*a* and *b*) on the monotonic background of the non-resonant detection. The position of the observed resonances in Figs. 1*a* and *b* can be estimated as

$$f = \frac{1}{4L_g}\sqrt{\frac{e(V_g - V_{th})}{m^*}}$$

where $(V_g - V_{th})$ is the gate voltage swing. The bars in Fig. 1*c* show the position and width of the experimental resonant maxima, and the line shows the calculated dependence of the resonant frequency against gate voltage. As seen, the theory reproduces qualitatively the change of the resonance position (V_g) with frequency of incoming radiation.

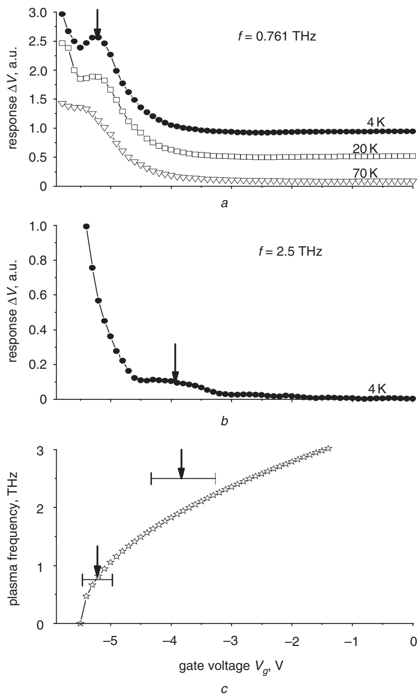

Fig. 1 *Transistor response, ΔV, against gate voltage; and plasma frequency against gate voltage*

a and *b* Response of GaN/AlGaN-based device to THz radiation against gate voltage for different temperatures and frequencies
c Bars show position and width of resonant maxima; line shows calculated dependence of resonant frequency against gate voltage

One of the most important parameters of the detectors is noise equivalent power (NEP), which can be found as N/R_V, where N is the noise of the transistor in V/Hz$^{0.5}$ and R_V is the responsivity in V/W. Fig. 2 shows the NEP for transistors with $L_g = 250$ nm at 300 K for frequencies of radiation $f = 0.2$ and 0.7 THz. The responsivity, which is the ratio of the output in volts to the radiant input in watts, was estimated in two different ways. For $f = 0.7$ THz, the responsivity was estimated as $R_V = \Delta V/(P_t S_a/S_t)$, where P_t is the total power of the source, S_t is radiation beam spot area, and S_a is the transistor area, which includes contact pads. In the experiment with 0.2 THz, the radiation was focused to the diameter approximately of the same size as the transistors, including the contact pads. Therefore, the total power of the source was taken for the NEP estimate. Since detection was studied at zero bias, the noise was taken equal to the thermal noise $N = \sqrt{4kTR_{FET}}$, where R_{FET} is the gate voltage dependent drain to source resistance, which can be extracted from the transfer current voltage characteristic of the field effect transistor. Fig. 2 shows the NEP at 300 K against gate voltage. The inset in Fig. 2 shows the responsivity for the 0.2 THz experiment as a reference. As seen, in spite of a relatively low responsivity, the minimum NEP is of the order of 5×10^{-9} W/Hz$^{0.5}$. The minimum NEP corresponds approximately to the voltage, where the responsivity is the largest. This value of NEP is slightly higher than for such commercial detectors as Golay cells, pyroelectric detectors and Schottky diodes, having, meanwhile, the potential advantage of operation at very high sampling frequency of several tens of gigahertz.

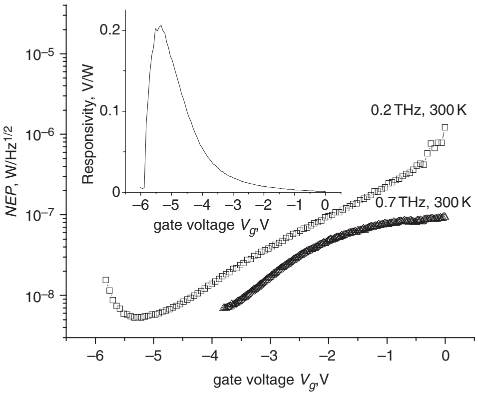

Fig. 2 *NEP against gate voltage (T = 300 K)*
Inset: Responsivity against gate voltage for $f = 0.2$ THz

Conclusions: We have investigated different GaN/AlGaN devices and demonstrated an efficient detection of electromagnetic radiation at THz frequencies. While varying the temperature in the range from 4 K to 300 K and the excitation frequency within 0.2–2.5 THz, we have shown the resonant detection due to excitation of the plasmon modes. These detectors demonstrate reasonably low noise equivalent power suitable for practical applications.

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