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Strained silicon modulation field-effect transistor as a new sensor of terahertz radiation

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Abstract
In this paper, we report on room temperature detection of terahertz radiation from strained-Si modulation-doped field-effect transistors. A non-resonant signal was observed with a maximum around the threshold voltage. The signal was interpreted due to the plasma wave nonlinearities in the channel. The intensity of the signal increases for the higher applied drain-to-source current. We also observed a dependence of the signal on the polarization of the incoming radiations.

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1. Introduction

The development of new optoelectronic devices for terahertz (THz) technology has been gaining interest over the last decade. The attractive features of THz radiation are as follows. (i) It is transmitted by clothes and most packaging materials such as paper or plastics. (ii) Many substances have 'fingerprint' spectra in the THz range. (iii) Due to its low photon energy (about one million times less than x-rays), THz radiation is non-ionizing and therefore not dangerous for human beings. Thanks to all those capabilities, THz systems are a promising tool for spectroscopy and imaging applications as well as future ubiquitous communication networks [1, 2]. In the early 1990s, Dyakonov and Shur predicted that collective charge density oscillations in two-dimensional electrons systems can be used for detection and/or for emission of THz electromagnetic radiations [3, 4]. Experimental investigations performed on different architectures of sub-micron transistors demonstrate their capabilities of emission and detection of THz radiation [5–10] which open the way for a new generation of THz devices. Non-resonant detection is one of the most promising results for THz applications. It was first observed on GaAs and GaN field-effect transistor [11] and later on silicon field-effect transistor (Si FET) [5]. High responsivity (200 V/W) and low noise equivalent power (NEP) (1 pW/$\sqrt{\text{Hz}}$) [12] were observed from Si-MOSFETs with different gate lengths (120 and 300 nm). THz imaging based on CMOS technology has been recently reported by different groups [13–15]. A 3×5 Si MOSFET focal-plane array processed by 0.25 μm CMOS technology was used by Lisauskas *et al* [13, 16] for imaging at 0.65 THz. A responsivity of 80 KV/W and a NEP of 300 pW/$\sqrt{\text{Hz}}$ were obtained. Recently, THz imaging has been performed by an nMOS field-effect transistor with an integrated bow–tie coupling antenna with a responsivity above 5 kV/W and a NEP below 10 pW/$\sqrt{\text{Hz}}$ [15].

The quality factor of the oscillation of the plasma waves is given by $Q = \omega\tau$, where $\omega = 2\pi f$ is the pulsation and $\tau = \mathrm{m}^*\mu/e$ is the momentum relaxation time proportional to the mobility (μ). The THz signal could be then strongly enhanced for high electron mobility devices. Strained-Si transistors are an alternative for THz application due to the following reasons. (i) Hall mobility measurement performed at room temperature shows that the mobility is higher in Si/SiGe n-channel devices [17, 18] than in conventional CMOS, (ii) high-frequency (HF) operation and noise performance are close to III–V ones (100 nm T-gate Si/SiGe n-MODFET shows high cut-off frequency (74 GHz) [19] and minimum noise figure as low as 0.3 dB at 2.5 GHz [20] has been reported), and (iii) Si/SiGe transistors can be made on Si wafers and are naturally wafer-compatible with mainstream CMOS technology. This fact is crucial to, for instance, integrate the read-out circuitry on the Si/SiGe THz sensor to build a SoC (System on a Chip). This will enable the Si/SiGe THz detection technology to benefit from the mature CMOS technology.

In this work, we investigated non-resonant detection of THz radiation by a strained-Si modulation FET. The device was subjected, at room temperature, to pulsed THz rays. The device exhibited a non-resonant detection with a maximum of the signal around the threshold bias. A dependence on the drain current and the polarization of the light are reported.

2. Devices description and experimental setup

The epistructure of the MODFET was grown by molecular beam epitaxy (MBE) on a thick relaxed SiGe virtual substrate grown by low-energy plasma-enhanced chemical vapor deposition (LEPECVD) over a p-doped conventional Si wafer. The final Ge molar concentration in the virtual substrate was $x_{\mathrm{Ge}} = 0.45$. The device had an 8 nm tensile strained (in terms of biaxial deformation) Si channel sandwiched between two heavily doped SiGe electron supply layers to generate a high carrier density in the strained-Si quantum well [17]. The ohmic contacts were not self-aligned. Two transistors were measured with different gate lengths (150 and 250 nm). The gate width and the source-to-drain length are 30 and 1 μm, respectively. The devices were excited at room temperature by a THz wave parametric oscillator (TPO) pulsed laser of 1.5 THz [21]. The TPO system consists of three mirrors and a MgO:LiNbO$_3$ crystal under non-collinear phase-matching conditions. It can emit a monochromatic THz wave over a wide tunable frequency range from 0.4 to 2.8 THz with a narrow line width lower than 100 MHz. The output power of the laser was 6 nJ/pulse for the 1.3–1.6 THz range and the repetition rate 500 Hz. The radiation was coupled to the dice via the metallization pads. The source terminal was grounded. The radiation intensity was modulated by a mechanical chopper at 1.29 KHz (figure 1) and the induced photoresponse signal is measured by using the lock-in amplifier technique. A wire grid polarizer was used to polarize the light in parallel with the channel. The principle of operation is as follows: when the device is excited by an external electromagnetic radiation, the induced ac electric fields can be converted into measurable dc signal via a nonlinear conversion mechanism. This is referred hereafter as the photoresponse signal.

3. Results and discussions

Figure 2 shows the photoresponse signal as a function of the gate bias for two devices with different gate lengths ($L_G = 150$ and 250 nm) excited by 1.5 THz radiation at room temperature. The signal is presented for different drain currents: 20, 50 and 100 μA. The intensity increases with the drain current as predicted by the theory [22, 23] and a maximum is observed around the threshold voltage. The same behavior has been recently reported by Elkhatib *et al* [24] demonstrating that the response signal increases linearly with the drain current (or drain-to-source voltage) and the responsivity might reach high within a saturation regime. The observed signal intensity is low because no parabolic mirror was used to focus the beam

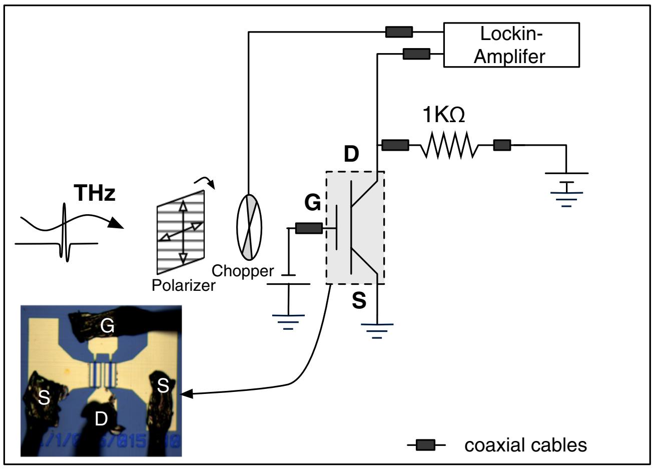

Figure 1. Schematic description of the experimental setup of the detection of THz radiation.

(This figure is in colour only in the electronic version)

and also, as reported in [17], the response intensity at Thz frequencies (over 1 THz) is considerably smaller than at sub-Thz ones (below 1 THz). The responsivity was estimated to be 20 V/J/Pulse at $I_{\mathrm{DS}} = 100$ μA. The device was also illuminated at 1.8 THz (figure 3); however, no resonance was observed. The observed difference on the intensity is related to the intensity of the incoming radiation which is slightly higher for 1.8 THz. A non-resonant response has been reported for Si-FET [5] and it was related to a low value of the quality factor, i.e. low mobility of the device. The quality factor was found to be around 1.2 for $\mu = 1355$ cm^2(V s)$^{-1}$ and $f = 1.5$ THz. This value is better than that in normal silicon; however, no resonance is observed which can be due to the low-efficiency coupling of the incoming radiations. Rumyantsev *et al* [17] obtained on similar devices a maximum value of the photoresponse signal when the beam focus was away from the transistor. This is a proof of low coupling of the THz radiation to the device. To increase the efficiency toward high non-resonant signal and possible resonant detection, new designs are under consideration: array of transistors, devices with larger pads and grating devices [25]. Even though the observed signal is low and non-resonant, our devices can operate as a broad-band detector of THz radiation at room temperature and they are suitable for THz spectroscopy.

Figure 4 shows the simulated photoresponse according to the following equation [5, 11]:

$$\Delta U = \frac{eu_a^2}{4ms^2}\left(\frac{1}{f(U_0,\kappa)} - \frac{1}{[f(U_0,\kappa)]^2[\sinh^2 Q + \cos^2 Q]}\right), \qquad (1)$$

where

$$f(U_0,\kappa) = 1 + \kappa \exp\left(-\frac{eU_0}{\eta K_B T}\right)$$

$$U_0 = Vg - V_{\mathrm{th}}$$

$$Q = \sqrt{\frac{\omega}{2\tau}\frac{L}{s}}.$$

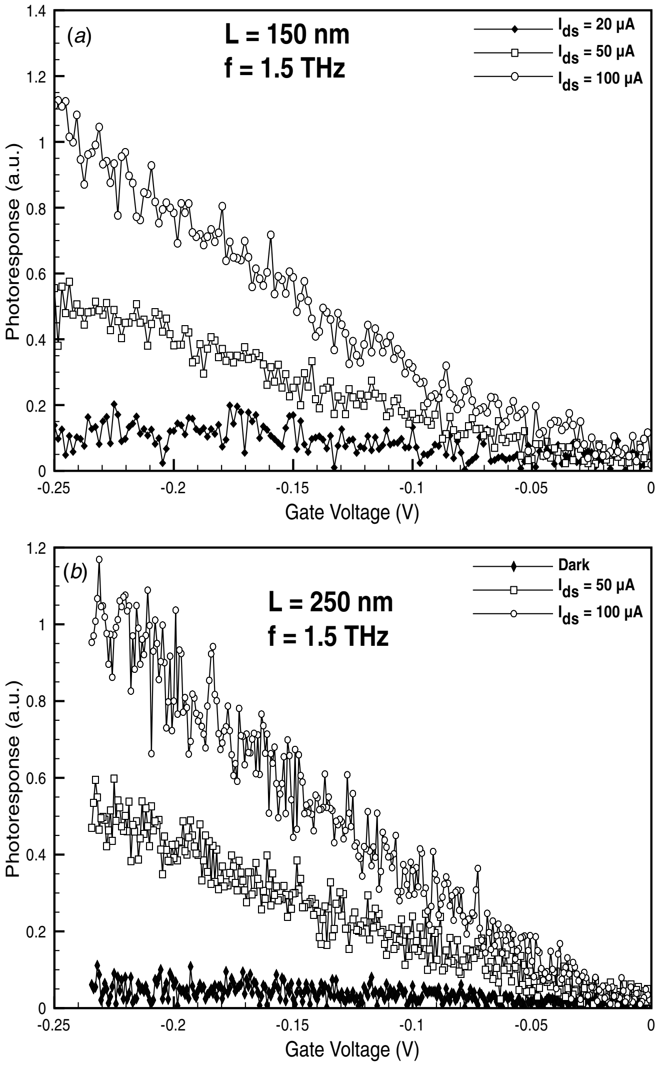

Figure 2. Photoresponse signal versus gate bias at 1.5 THz for two devices: (a) L_G = 150 nm and (b) L_G = 250 nm.

Here, κ is a dimensionless parameter related to the leakage current and s is the plasma wave velocity given by

$$s^2 = s_0^2\left[1+\exp\left(-\frac{e(V_g - V_{\rm th})}{\eta k_B T}\right)\right] \times \ln\left[1+\exp\left(\frac{e(V_g - V_{\rm th})}{\eta k_B T}\right)\right]. \tag{2}$$

The parameters η and $V_{\rm th}$ are related to the electron density in the sub-threshold region. In the present case, $V_{\rm th}$ was fixed at −0.26 V and the plot shows the case of three values of the parameter η = 0.1, 0.5 and 1. The electron concentration in the FET channel is given by [11]

$$n = n^* \ln\left[1+\exp\left(\frac{eU_0}{\eta k_B T}\right)\right],$$

where $n^* = C\eta k_B T/e^2$, with C being the gate capacitance per unit area and η being the ideality factor related to electron density (indirectly to current). The simulation can smoothly reproduce the experimental results.

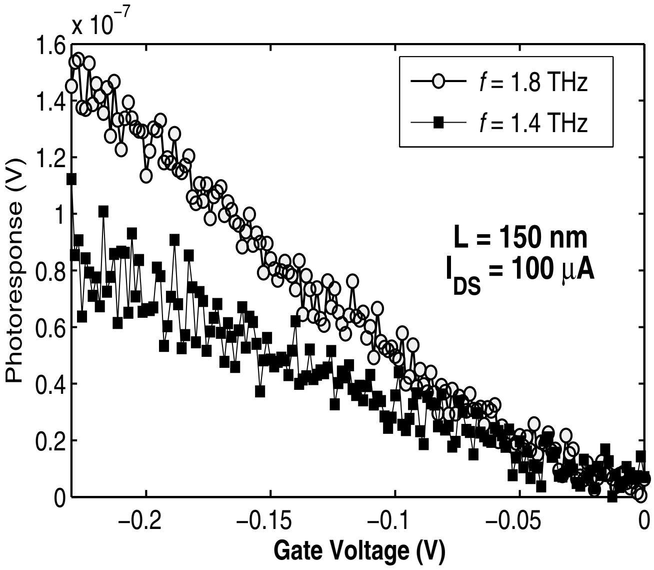

Figure 3. Photoresponse versus gate bias for different incoming THz frequencies (1.4 and 1.8 THz).

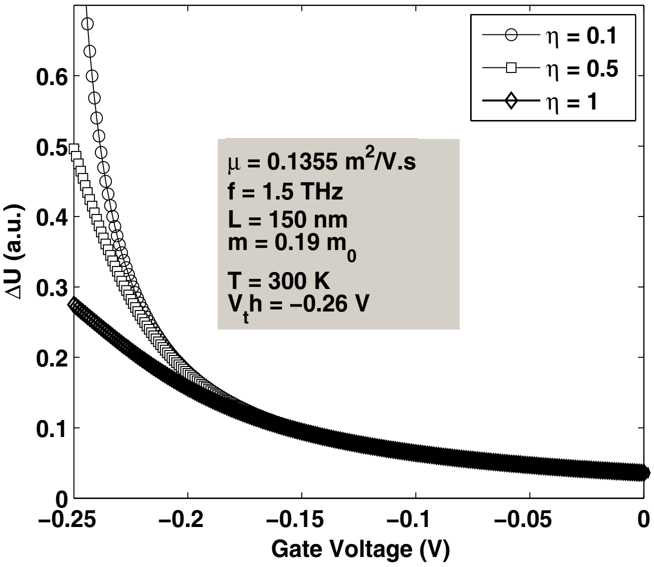

Figure 4. Simulated photoresponse signal for three different η parameters. Other parameters values are shown in the graph.

The incoming radiation was polarized using a controlled grid-wire polarizer and the polarization direction is defined by the orientation of the polarizer (figure 1). The device on the sample holder was tilted and the angle of 60° is the position where the grid is parallel to the channel. The photoresponse signal was measured for each angular position of the polarizer. Figure 5 depicts the maximum intensity signal obtained around the threshold bias for each angle. It is clearly seen that a maximum of the signal results when the incoming radiation is polarized along the channel. We can conclude that a maximum signal can be achieved for a polarization parallel to the channel.

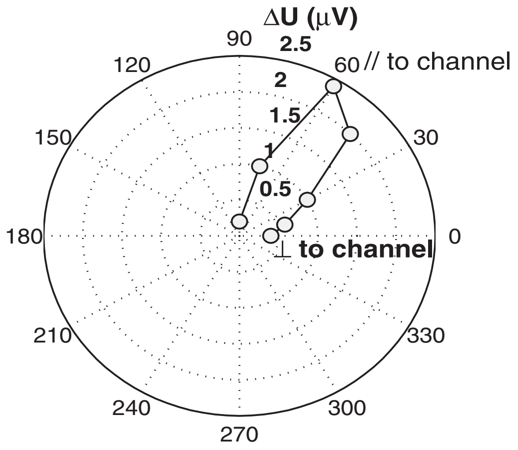

Figure 5. Photoresponse signal as a function of the polarization of the incoming radiation.

4. Conclusions

We reported on non-resonant detection of THz radiation from a strained-Si modulation-doped field-effect transistor. The detected signal was interpreted due to plasma wave nonlinearities in the channel. The intensity of the signal increases for the higher applied drain-to-source bias. The responsivity was estimated around 20 V/J/Pulse. Parallel polarization of the incoming radiation to the channel maximizes the signal.

Acknowledgments

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