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# Enhancement of sub-terahertz detection by drain-to-source biasing on strained silicon MODFET devices

Y.M. Meziani<sup>1</sup>, S. Morozov<sup>2,4</sup>, J.A. Delgado Notario<sup>1</sup>, K. Maremyanin<sup>2</sup>, J.E. Velázquez<sup>1</sup>, K. Fobelets<sup>3</sup>

<sup>1</sup> Departamento Física Aplicada, Universidad de Salamanca, 37008 Salamanca, España.

<sup>2</sup> Institute for Physics of Microstructures of Russian, Academy of Sciences, 603950, GSP-105, Nizhny Novgorod, Russia.

<sup>3</sup> Department of Electrical and Electronic Engineering, Imperial College, London SW7 2AZ, UK.

E-mail: meziani@usal.es

**Abstract.** We report on non resonant detection of sub-terahertz radiation (148-353 GHz) using strained silicon modulation field effect transistor with different gate lengths. The devices were excited at room temperature by a Backward Wave Oscillator (BWO) source. Enhancement of the photoresponse signal by drain-to-source bias was observed. Increasing drain-to-source voltage leads to asymmetry between the boundary conditions at the source and drain contacts.

## 1. Introduction

Development of terahertz sensors compatible with mainstream CMOS technology is of big interest due to its capabilities for different terahertz applications like security, imaging, and inspection [1, 2, 3]. Terahertz rays are located in the spectral region 0.1 – 10THz (3mm – 30 $\mu$ m, 3 – 300cm<sup>-1</sup>) between the microwave and the infrared portion of the electromagnetic spectrum [4]. In early 1990's, Dyakonov and Shur [2] theoretically demonstrated the possibility of using sub-micron field effect transistors as detectors of terahertz radiation by means of the oscillations of plasma waves in the channel. Those devices present many advantages: low cost, small size, room temperature operation and possible tuning by mean of gate bias. Experimental and theoretical investigations have been conducted in semiconductor devices, demonstrating their capabilities for detection of terahertz radiation. Experimental non resonant detection (broadband detection) was demonstrated using different types of transistors like GaAs/AlGaAs FETs [5, 6] and Si-MOSFET [7, 8]. A responsivity of 80 kV/W and a NEP (Noise Equivalent Power) of 300 pW/Hz<sup>1/2</sup> as well as imaging at 0.65 THz were reported using an array of Si-MOSFET processed by 0.25  $\mu$ m CMOS technology [9]. Recently, asymmetric double grating gates devices based on GaInAs/InP HEMTs have shown a record of responsivity and NEP of around 20 kV/W and 0.48 pW/Hz<sup>1/2</sup>) [10, 11].

In the present paper, we have studied the detection of sub-terahertz radiation by using Strained

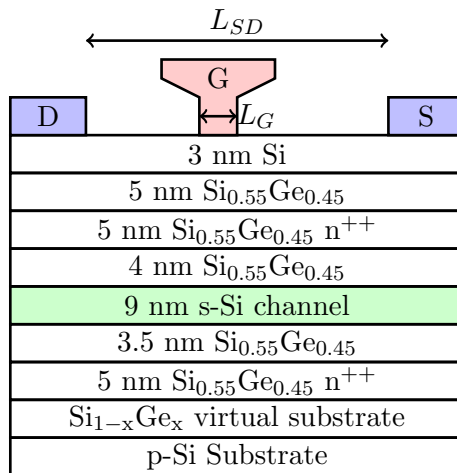
<sup>4</sup> Also with: Lobachevsky State University of Nizhni Novgorod, 23 Gagarin Avenue, Nizhny Novgorod,603950, Russia



Silicon MODFET at room temperature and under drain-to-source bias. Two Si-MODFET devices were excited by a BWO at different frequencies, the response exhibits a non-resonant feature with a good signal to noise ratio. For the first device, with better performance, an abrupt increase of the responsivity was observed. This was attributed to the asymmetry between the boundary conditions at the source and drain contacts.

## 2. Strained Silicon MODFET and experimental setup

The epistructure of the MODFETs used in this work 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 (Fig. 1). The final Ge molar concentration in the virtual substrate was  $x_{Ge} = 0.45$ . The device had a 9 nm tensile strained (in terms of bi-axial deformation) Si channel, sandwiched between two heavily doped SiGe electron supply layers to generate a high carrier density in the strained-Si quantum well [12]. The ohmic contacts were not self aligned. Table 2 shows the geometry of two transistors with different gate lengths (100 nm and 250 nm). More details on the epistructure can be found in ref. [13].



**Table 1.** Epistructure of the MODFET

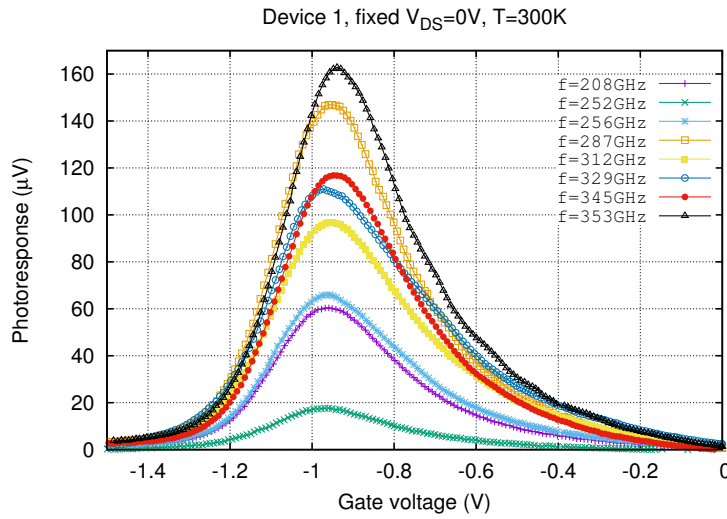
Two BWOs were used for the detection experiments. The first one with tunable frequency from 142 to 248 GHz and the second one with frequencies 286 to 353 GHz. The incoming radiation intensity was modulated by a mechanical chopper at 1.29 kHz and coupled to the device via the contact metalization pads. The induced photoresponse signal was measured by using a lock-in amplifier technique. More description of the experimental setup can be found in [7].

## 3. Results and discussions

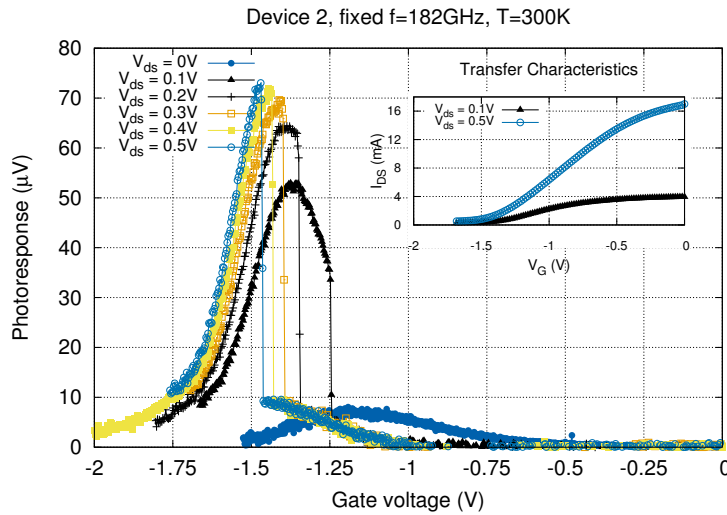
The photoresponse signal measured for the device 1 (table 2) with  $L_G = 250$  nm is shown in figure 1 versus gate bias at different frequencies from 208 to 353 GHz. The signal was measured at room temperature and at fixed  $V_{DS} = 0V$ . Good level of signal to noise ratio was obtained with a maximum around the threshold voltage ( $V_{th} \simeq -0.9V$ ). The latter is related to the non-resonant detection caused by over-damped plasma waves that generate into space-charge waves. The intensity of the signal however, do depend on the incoming radiations frequencies. The maximum is obtained at 353 GHz and the minimum at 252 GHz. This behavior can be attributed to the fluctuation of the emitted power from the BWO sources for different frequencies and also to a better coupling of the incoming radiation to the device at the specific frequency in

	$L_{SD}$ ( $\mu m$ )	$L_G$ ( $nm$ )	$W_G$ ( $\mu m$ )
Device 1	2	250	80
Device 2	1	100	80

**Table 2.** Geometry parameters of devices.



**Figure 1.** Photoresponse signal vs. gate bias at different incident radiations frequencies from 208 to 353 GHz. It was obtained for device 1 at room temperature and at fixed  $V_{ds}=0V$ .



**Figure 2.** Photoresponse signal vs. gate bias under different drain-to-source biasing ( $V_{ds}$  from 0 to 0.5 V). Experiment performed on Device 2 at room temperature and under electromagnetic radiation at 182 GHz. Inset shows the transfer at  $V_{ds}=0$  and 0.5 V

agreement with the theory. Tuning the frequency is obtained by increasing the cathode voltage of the Magnet (1-5 kV), it's difficult to maintain the emission power constant for all frequencies and it fluctuates from 1 to 10 mW [14].

For device 2 (table 2), the photoresponse signal is shown in figure 2. Inset of figure 2 shows its transfer characteristic for two values of the drain-to-source voltage  $V_{ds}=0.1$  and 0.5 V, for which value of  $V_{th} \simeq -1.4V$  was extracted. At a fixed  $V_{ds} = 0.1V$ , the maximum photoresponse was observed around -1.2 V with an intensity around  $10\mu V$ . When  $V_{ds}$  was increased to higher voltages (up to 0.5 V), the intensity of the signal was increased by several orders with an abrupt increase of the signal. The estimated responsivity  $R_v$  was calculated using the following equation [10]:

$$R_v = \frac{S_t \Delta U}{S_d P_t} \quad (1)$$

where  $\Delta U$  is the measured photoreponse signal,  $P_t$  is the total power of the THz radiation in the detector plane (the power was  $\simeq 0.15$  mW lower than the emitted one from BWO because of the attenuation in atmosphere),  $S_t$  is the spot size of the radiation beam ( $\simeq 3$  mm), and  $S_d$  is the active area of the detector. A responsivity of  $\simeq 2$  kV/W and 20 kV was obtained for

$V_{ds}=0$  and 0.5 V, respectively. This clearly shows an increase of the responsivity by two orders of magnitude induced by  $V_{ds}$ . Similar effect was observed by Lu et al. [15] on a GaAlAs/GaAs HEMT related to the asymmetry of the boundary condition induced by  $V_{ds}$ . The gate-to-drain capacitance  $C_{GD}$  decreases as function of  $V_{ds}$  and the gate-to-source capacitance ( $C_{GS}$ ) increases and it saturates for higher values of  $V_{ds}$  [15]. This behavior induces a greater asymmetry degree in the boundary conditions of the plasma waves and greatly enhances the responsivity of the detector. The abrupt increase of the photoresponse may be attributed to carrier transfer to a parasitic channel above the upper supply layer, but further investigation needs to be carried out to fully understand the phenomenon.

## Conclusion

We report on enhancement of the photoresponse signal as well as the responsivity of the detector by means of drain-to-source bias. An abrupt increase of the signal was observed and an enhancement of the responsivity by two orders was demonstrated. This was related to the the asymmetry between the boundary conditions at the source and drain contacts.

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