Experimental and theoretical studies of Sub-THz detection using strained-Si FETs

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Abstract. We report on experimental and theoretical studies of nanoscale gate-lengths strained Silicon MODFETs as room temperature non resonant detectors. Devices were excited at room temperature by an electronic source at 150 and 300 GHz to characterize their sub-THz response. The maximum of the photovoltaic response was obtained when the FET gate was biased at a value close to the threshold voltage. Simulations based on a bi-dimensional hydrodynamic model for the charge transport coupled to a Poisson equation solver were performed by using Synopsys TCAD. A charge boundary condition for the floating drain contact was implemented to obtain the photovoltaic response. Results from numerical simulations are in agreement with experimental ones. To understand the coupling between terahertz radiation and devices, the devices were rotated at different angles under excitation at both sub-terahertz frequencies and their response measured. Both NEP (Noise Equivalent Power) and Responsivity were calculated from measurements. To demonstrate their utility, devices were used as sensors in a terahertz imaging system for inspection of hidden objects at both frequencies.

1. Introduction
The development of novel materials, concepts and device designs for terahertz radiation detection using semiconductors has recently fuelled the research of room temperature THz detectors. In early 90’s, Dyakonov et al.[1] theoretically demonstrated the possibility of using sub-micron field effect transistors (FETs) as detectors of terahertz radiation by means of the oscillations of plasma waves in their channel in frequency ranges far beyond the transistor cut-off frequency (fT). FET devices present many advantages: low cost, small size, room temperature operation and high-speed response that make them highly competitive with other THz detection technologies.

Room temperature detection of sub-terahertz radiation has been demonstrated by using different types of transistors such as commercial GaAs FETs and Si-MOSFET. In the present work, we investigated room temperature terahertz detection using Strained-Silicon Modulation Field Effect transistors (s-Si MODFET) with different gate lengths. As Schottky gated s-Si MODFETs exhibit higher values of channel electron mobility (≈ 1400 cm²V⁻¹s⁻¹) than conventional Si-MOSFET (≈ 200 cm²V⁻¹s⁻¹), they are excellent candidates to detect THz radiation, while offering many of the
advantages of Si devices. The natural substrate compatibility of s-Si MODFETs with conventional Si technologies is a key benefit of the system Si:SiGe to compete in future on-chip THz system integration.

2. Device and TCAD Modeling
In this work, we studied n-channel s-Si/SiGe MODFETs as sub-THz detectors. The material system Si/SiGe allows the creation of a thin layer of strained silicon under tetragonal (biaxial tensile) strain. This strain has significant impact on the FET channel mobility of the semiconductor. The epistucture of the MODFETs used in this work is described in [2] and it is given in Fig. 1(a). All devices had a T-shape design [Fig. 1(b)] and were mounted on the same dual inline package (DIL14).

![Figure 1. (a) Epi-structure of devices (b) T-shape design and devices on DIL14 with a microscope image of the devices.](image)

Table 1 shows the geometrical parameters of the three set of transistors studied; a typical transfer characteristic is presented in the inset of Fig. 2(a).

| Device | L_SD (µm) | L_g (µm) | W_SD (µm) | NEP (pW/Hz$^{0.5}$) | R_v (V/W) | NEP (pW/Hz$^{0.5}$) | R_v (V/W) |
|--------|-----------|----------|------------|----------------------|-----------|----------------------|-----------|
| Device 1 | 2 | 100 | 80 | 158 | ~10 | 520 | 3 |
| Device 2 | 2 | 150 | 80 | 125 | 15 | 546 | ~4 |
| Device 3 | 2 | 500 | 80 | 400 | ~10 | 430 | ~10 |

Table 1. Geometrical parameters of the Si MODFETs along with measured and calculated NEPs and R_v.

A 2D numerical study was performed to understand and predict the response of the devices. Owing to the nature of the carrier transport in submicron length gate devices, we used a hydrodynamic (2DHD) model for the majority carriers (electrons) self-consistently coupled to a two-dimensional solution of the Poisson equation. The study of the THz photovoltaic response of the transistors was implemented in Synopsys TCAD, as in measurements: the source was grounded and the gate was DC-biased, while floating the drain contact. A full description of the methods used for calculations could be found in [3].

3. Results and discussions
The devices were excited at room temperature by a dual-frequency electronic source based on frequency multipliers. The source frequencies were 150 and 300 GHz with output power levels of 3 mW and 6 mW respectively. The incoming radiation was modulated by a mechanical chopper between
233 Hz and 1.29 KHz. Induced photoresponse was measured by using the lock-in technique. Typical obtained photoresponses signals vs gate voltage are shown in Fig. 2 (a) for device 1 with Lg = 100 nm under excitation of 150 GHz (blue square symbols) and 300 GHz (blue dotted symbols). Figure 2 (b) gives the simulated photovoltaic response of the same device as in Fig. 2(a) when it was excited at several frequencies in the range 0.1-1THz. The shapes of both signals are similar and maxima are obtained around the devices’ threshold voltages. This behavior is explained as non-resonant (broadband) detection that must be attributed to low values of the quality factor (Q=ωτ<1). Quality factor was estimated to have a value close to 0.13 at 150 GHz and 0.27 at 300 GHz.

![Figure 2](image-url) (a) Photoresponse vs. gate voltage under excitation at 150 GHz (red square) and 300 GHz (blue dotted). Inset shows the corresponding transfer characteristics. (b) Simulated photoresponse vs. gate voltage under excitation at different frequencies for Device 1 with Lg = 100 nm.

In order to understand how radiation is coupled to the devices we studied the photoresponse as a function of the polarization of the incoming radiation. It is clearly seen at low frequencies (150 GHz) bonding wires and contact pads could play the antenna role showing the maximum response at different angles (Fig (3). We observed that for devices with Lg=100 and 150 nm, only two lobs were observed and for device with higher gate length (Lg=500nm) different maximum were observed at different angles. Since the area is much bigger for this device, the coupling could be performed by both the bonding wires as well as the gate pads fingers.

![Figure 3](image-url) Figure 3. Photoresponse vs. rotation angle for all devices under excitation of 150 GHz.

Responsivity (Rr) as well as the Noise Equivalent Power (NEP) are the key parameters to determine the performance of these detectors’ NEP and R are calculated by the formulas described in [4]. For the calculations the power incident at the detector position was 0.5/1 mW at 150/300 GHz. Table 1 summarizes the obtained NEP and Rr for the studied devices at 150 and 300 GHz. Device 2
with Lg = 150 GHz shows the best performance at 150 GHz. This must be attributed to a larger photoresponse signal exhibited by this device and to a better coupling with the incoming THz radiation. Those obtained values of NEP and Rv are comparable to the commercial room temperature THz detectors like Golay cells, pyroelectric detectors, and Schottky diodes. However, the Si-MODFET presents the advantage of being able to work at higher values of the modulation frequency (higher than 5 kHz).

To demonstrate its usefulness for practical applications, the detectors were used as the sensor within a THz imaging system. Figure 8 shows the THz images obtained at 150 GHz and 300 GHz as well as the visible one. Better resolution was obtained at 300 GHz which is related to its lower wavelength (λ=1mm).

![Figure 4. Visible image (left) and terahertz ones (right) at 150/300 GHz obtained at room temperature with Device 3 with Lg = 500 nm.](image)

4. Conclusions
We report on a non-resonant detection of sub-THz radiation at 150 and 300 GHz at room temperature by using s-Si MODFETs with different gate lengths. Simulations results based on 2D numerical studies with Synopsys TCAD show a non-resonant response in agreement with experimental measurements. We have shown that gate pads are playing the role of antenna to couple the THz radiation at high frequencies. Competitive values of the performance parameters (NEP and Rv) were obtained. The practical use of these detectors for inspection of hidden objects was demonstrated.

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