

TCAD study of sub-THz photovoltaic response of strained-Si MODFET

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Abstract. This paper reports on a bi-dimensional TCAD study of the sub-THz response of strained-Si MODFETs. A charge boundary condition for the floating drain contact was implemented to obtain the photovoltaic (PV) response of the device. A non-resonant THz PV response was obtained in agreement with theoretical and experimental works. A main result of this study is that the PV response is strongly influenced by both the gate length and the gate topology. In particular, it was found that a dual-finger gate gives the maximum response at 300GHz.

1. Introduction

During the past two decades a considerable effort was devoted to the development of Field-Effect Transistors (FETs) using the Si/SiGe material system. N-channel strained-Si FETs with buried [1] (s-Si MODFET, modulation doped FETs) and surface channels [2] (s-Si MOSFET) were developed. Minimum noise figures as low as 0.4dB at 2.5GHz and cut-off frequencies (f_T) in excess of 70 GHz at 300K were achieved in s-Si MODFET [3]. A number of analog building blocks were demonstrated [4], nevertheless, the final break through the market of these technologies was hindered by low-yields of global-strain wafers. Recently, it has been shown the potential of s-Si MODFETs as room temperature detectors of sub-THz radiation [5, 6], i.e. in frequency ranges far beyond f_T . As Schottky-gated s-Si MODFETs exhibit large values of channel electron mobility ($\approx 2,000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, [7]) they can be used as detectors of THz electromagnetic radiation [8]. This has been experimentally demonstrated and the mechanism of detection identified as the excitation of resonant or overdamped plasma waves in the two-dimensional electron plasma in the device channel [6].

2. Device description and models used in simulation

In this work, we simulated n-channel s-Si MODFETs. Devices had a thick SiGe virtual substrate over a p-Silicon wafer. The final Ge molar concentration in the virtual substrate is 0.3. The device has a 10 nm tensile strained (in terms of biaxial deformation) Si channel, sandwiched between two heavily doped SiGe electron supply layers (doped at $\sim 10^{19}$ the top supply layer and $\sim 10^{18}$ the bottom one) to generate an electron dual-channel in the strained-Si quantum well. The structure of the simulated device is shown in the left plot of Fig 1 along with the energy band diagram calculated using Taurus-Medici [9]. The transistor was studied with different gate lengths (L_G) in the range 50 nm to 500 nm



while keeping constant the Source-to-Drain distance (L_{SD}) at 2 μm . The source-to-gate length (L_{SG}) was modified to study the effect of asymmetry in the device by changing the position of the gate.

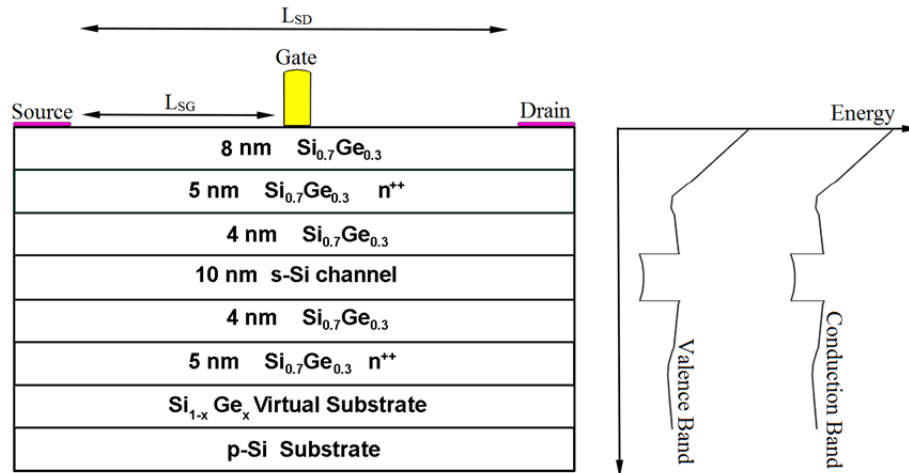


Figure 1. Vertical layout of the (left) and energy band diagram (right) of the MODFET under study.

A 2D numerical study was performed using Synopsys TCAD to understand the response found in THz measurements. Modeling the electrical behavior of transistors with deep-submicron gates needs an accurate description of the complex nature of the carrier transport in the channel. To this aim we used a two-dimensional hydrodynamic (2DHD) self-consistently coupled to a two-dimensional solution of the Poisson equation. In the 2DHD simulations impurity de-ionization, Fermi-Dirac statistics and mobility degradation due to both longitudinal and transverse electric field were taken into account. The source and drain regions were simulated as non-self-aligned implanted contacts.

The study of the THz photovoltaic (PV) response of the transistor was implemented by biasing source and gate and floating the drain contact while, as in measurements, a sub-THz sinusoidal signal was superimposed to the gate voltage as described in [8]. The amplitude of the gate signal was fixed to 5mV; the induced drain voltage exhibit both the same shape (sinusoidal) and frequency of the gate AC voltage ensuring that no frequency conversion takes place but its amplitude is considerably smaller than the one of the gate's signal as in the sub-THz range the device is unable to amplify signals, additionally the mean value of the induced drain voltage were negative in good agreement with the theoretical model [8]. The charge boundary condition for the floating is specified as:

$$\oint \vec{D} \cdot d\vec{S} = Q$$

where $\vec{D}$ is the displacement vector, Q is the total charge and the integral is evaluated over the drain contact surface.

Table 1. Electrical parameters of the s-Si MODFETs.

	Simulated structures			
L_G (nm)	50	100	250	500
V_{th} (V)	-1.2	-0.9	-0.75	-0.675
g_m (mS/mm)	72	98	112	105
$g_{m,exp}$ (mS/mm)	-	66	76	74
f_T (GHz)	36	31	22	11

3. Results and discussion

Table 1 summarizes the most relevant DC and AC parameters obtained in simulations. The second row gives the threshold voltage (V_{th}). The third and fourth rows contain the maximum values of the transconductance obtained in simulations and in measurements, respectively. The differences found in transconductance are attributed, essentially, to differences in contact resistances and implantations between the simulated and the actual transistors.

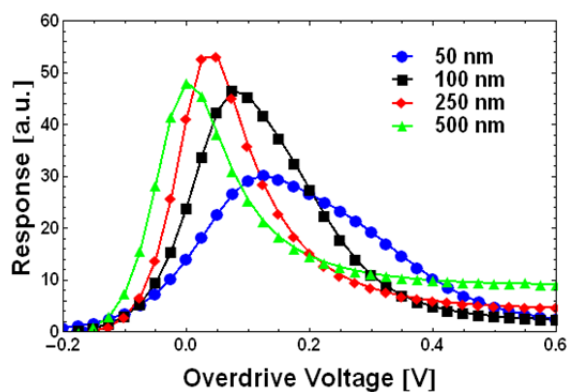


Figure 2. PV response of s-Si MODFET with different gate-lengths under THz excitation of 300GHz vs. gate overdrive.

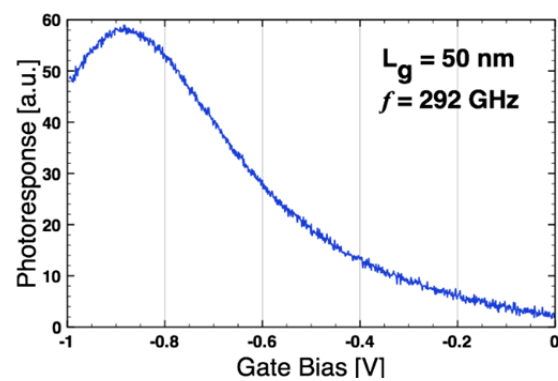


Figure 3. Experimental PV response of a s-Si MODFET with $L_g=50$ nm under THz excitation of 292GHz [10]. The value of the threshold voltage was $V_{th} \approx -0.84$ V.

The gate structure is a key design parameter to enhance the responsivity of FETs as THZ sensors. Figure 2 gives the simulated PV response of the four simulated transistors when excited at 0.3THz. Results show a non-resonant response in agreement with theoretical [8] and experimental results (see Fig. 3 [10]).

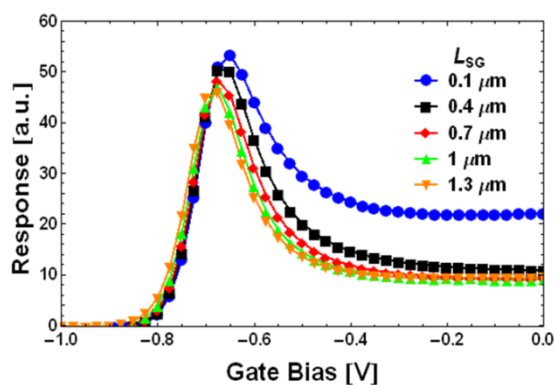


Figure 4. PV response of a 500-nm gate transistor placed for four different values of L_{SG} (under a 300GHz excitation).

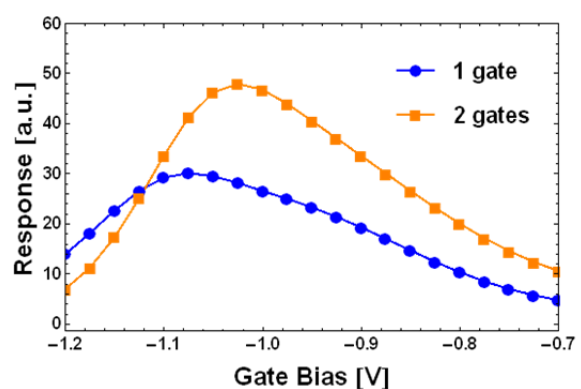


Figure 5. PV response of a 50-nm gate transistor for a gate with 1 and 2 fingers equally distributed between source and drain (under a 300GHz excitation).

Following the same trend as transconductance, the THz PV response exhibit lower values as the gate is shortened owing to a weakened channel control by the gate. The main conclusion to be drawn from Fig. 2 is that neither self-aligned structures, nor very short gate lengths will lead to optimum structures in terms of the THz photoresponse. We also found a significant dependence of the PV maximum with the excitation frequency.

Figure 4 gives the PV response of a MODFET when its 500-nm gate is placed at different distances (L_{SG}) from the source contact: only marginal changes in the PV response are obtained; in strong contrast to some commonly accepted ideas, an asymmetric gating of the channel will not necessarily lead to significant enhancements of the THz response. On the contrary, changes of the gate topology, such as a grating of the gate, has a significant impact on the THz PV response in agreement with FDTD (Finite Differences Time Domain) calculations using a simpler model for the electrons transport in the channel [11]. In Fig. 5 the PV response of s-Si MODFETs with two configurations of the gate is given. A large enhancement, close to 60%, of the PV response is found using a two-finger gate as compared to a single-finger gate transistor.

Conclusions

A 2D TCAD study of strained-Si MODFETs is performed to investigate their sub-THz photovoltaic (PV) response. To this aim a charge boundary condition for the floating drain contact was implemented. In agreement with measurements, a non-resonant sub-THz PV response is found for the simulated devices. A main result of this study is that the PV response is strongly influenced by both the gate length and gate topology. As the maximum PV response changes with both gate length and excitation frequency a careful design of the device is needed to optimize the device parameters (such as its gate length) to obtain a maximum of PV response. In particular, it was found that a dual-finger gate is suitable to obtain maximum response at 300GHz.

Acknowledgement

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