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Silicon MOSFETs As Room Temperature Terahertz Detectors

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Abstract. Because of their competitive Noise Equivalent Power (NEP) at room temperature and their fast modulation frequency, Field Effect Transistors (FETs) are one of the most promising devices for room temperature multipixel THz detection and imaging. We report here on an experimental study of the sub-THz detection as a function of the gate length in Silicon FETs and discuss the physical basis of their optimisation.

Backgrounds
In 1990, Dyakonov and Shur proposed that two dimensional transistor channel could be used as a cavity for plasma waves excited by current flow or incident radiation [1, 2]. The frequency of emitted or detected electromagnetic radiation in such a way for transistors of nanometer size is in the THz frequency range. The detection of radiation is due to the nonlinear properties of the transistor channel: the ac current induced by the incoming radiation is rectified and a photoresponse in the form of a dc voltage between source and drain appears.

Here we deal with sub-THz detection into Silicon FETs. In this particular material, because of low electron mobility and relatively low incident frequency, plasma waves in the channel are overdamped [3]. As it was shown theoretically, this nonresonant detection is characterized mainly by a single parameter: a critical length, which describes the exponential decay of the plasma wave amplitude with the distance [4].

Experimental details
We studied fully depleted nMOS transistors fabricated on biaxially strained SOI (here tensile strain). The thickness of the buried oxide (BOX) was 20 nm, silicon layer thickness Ts, was 8 nm. Gate stack consisted of 2.5 nm HfZrO₂ layer deposited by atomic layer deposition method and covered by a 5 nm TiN metal gate and 80 nm of polysilicon.

Studied devices had the channel width \( W_g = 10 \, \mu m \), the channel length, \( L_g \), was in the range from 50 nm to 10 \( \mu m \). The mobility for transistors with \( W_g \gg L_g \) was determined by the magneto resistance method [5,6]. The channel depletion threshold voltage is near 0.2 V, and channel resistance is decreasing linearly with its length.
The photoresponse measurements were performed using a Back Wave Oscillator (BWO) at 230 GHz and output power of few mW. The FETs were mounted on an X-Y two-dimensional stage controlled by a computer and placed at a distance of 10 mm from the BWO output horn and the electric field of the incoming radiation was parallel to the source-drain direction. The spatial intensity information was preliminary collected at the same distance by a pyroelectric detector. The radiation intensity was mechanically chopped (300-1000 Hz range), and the open-circuit source drain voltage was measured using a lock-in technique. All measurements were done at room temperature.

Results and discussion.

The electron mobility was about 300 cm²/(V.s) for gate length higher than 0.1 µm and then decreased to 180 cm²/(V.s) for 55 nm gate length. This type of dependence of electron mobility on the gate length, \( \mu(L) \), had been described and discussed previously in reference [5].

Figures 1 below shows the photoresponse of a whole set of FETs, with different gate lengths (varying from 50 nm, up to 10 µm), versus the gate swing voltage \( U_0 \) where \( U_0 = U_g - U_{th} \) with \( U_g \) is the gate voltage and \( U_{th} \) the threshold voltage. One can see that the photoresponse is a decreasing function of the gate swing voltage for \( U_0 \geq 0 \). This behavior is characteristic for the non resonant detection and it has been observed for different materials (see, for example, [3]).

![Photoresponse of transistors versus gate swing voltage.](image1)

**Figure 1.** Photoresponse of transistors versus gate swing voltage.

One can also see that the gate length significantly influences the photoresponse amplitude: for the long devices the amplitude is much higher than for the short ones. The photoresponse versus gate length is presented in Figure 2.

![Photoresponse of transistors versus gate length.](image2)

**Figure 2.** Photoresponse of transistors versus gate length.
The black points are experimental values of photoresponse, taken in the range 0.1-0.25 V of the gate voltage swing, where signal has a 1/U₀ shape described by the broadband-detection theory [3]. At smaller values of gate voltage swing the resistance of the transistors strongly increases and results can be influenced by impedance mismatch with measurement equipment [7]. As it is seen, the photoresponse strongly increase with the gate voltage increasing, then at Lg=250 nm it becomes saturated.

The detection regime depends on the parameter ωτ and on the gate length Lg [4]. As the mobility in our samples (μ< 350 cm²V⁻¹s⁻¹) and the radiation frequency (f ≈ 230 GHz) are rather low, the parameter ωτ is much lower than unity, and the plasma waves in the channel are overdamped along the channel.

In this case, photoinduced voltage is given by [4]:

\[
U(x) = \frac{U_0^2}{4U_0} \left[1 - \exp(-2x/l_c)\right]
\]

(1)

Where x is the distance from the source, U₀, the amplitude of the ac modulation due to the incident radiation on the FET, U₀ is the gate voltage swing and l_c is the characteristic length for the decay of the ac voltage (and current) away from the source, also given by l_c = s(2τ/ω)¹/² ,with the plasma waves velocity s = (eU₀ / μm)¹/². Using the set of parameters U₀ = 0.25 V, μ = 0.03 cm²V⁻¹s⁻¹, and f = 230 GHz, we obtain the l_c = 100 nm.

In the case of short gate transistors, Lg < L_c, the ac current due to the incident radiation goes through the gate-to-channel capacitance practically uniformly on the whole length of the gate, and just a part of the photoresponse dc voltage is built up. On the contrary, in the case of long gate transistors with Lg >> L_c, the ac current will leak to the gate before it achieves the drain, and the total photoresponse is built up. This can be illustrated by plotting the photoresponse signal versus gate length of transistors (see Figure 2).

The blue solid curve is a fit of experimental results, using equation 1, with a fixed critical length of l_c = 100 nm. The red curve with stars, is a fit of experimental results using equation 1 also, but taking into account that a) the effective gate length is 15 nm shorter than nominal ones (due to the implant pocket zones), and b) that the mobility also depends on the gate length ([6]). One can see that the theoretical estimation is in a relatively good agreement with experimental results.

Conclusion
In this paper we investigated THz detection by Silicon FETs. We found that the dependence of the photoresponse on the gate length is well described by the theory. We established, that for this type of detection (broadband at low frequency regime) the channel length should be at least several times the critical length which is defined by the incident frequency and carrier mobility. This supplementary information will allow to optimize the design of Terahertz detectors based on Si-MOSFETs technology. Because of their competitive NEP and their fast modulation frequency, these improved detectors could be used in arrays for real time imaging applications at room temperature (THz camera) [7].
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