Investigation of Single Pixel DePMOSFETs under Cryogenic Conditions

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Abstract—The observation of astrophysical objects in the mid-infrared requires Blocked Impurity Band (BIB) detectors based on n-doped Silicon. Because of the low binding energy of the shallow impurities (42 meV to 54 meV), infrared radiation in the electromagnetic spectrum of 10 to 40 microns can excite electrons from the shallow impurities into the conduction band. To ensure the occupation of these impurities and to prevent high leakage current the BIB detector has to be cooled down to 5 K to 10 K. It is desirable to observe faint astronomical objects with such a detector, which can be achieved with a high Signal to Noise ratio. One possibility is an implemented DePMOSFET [1] on the BIB detector in order to be free of interconnection stray capacitance.

We investigate the DePMOSFET at a temperature scale from 300 K down to 5 K. We show first results of characteristic and dynamic measurements of the single pixel DePMOSFET at low temperature. We irradiate the single pixel with a $^{55}$Fe source and take a spectrum of the $K_{\alpha}$- and $K_{\beta}$-line. The clear mechanism is investigated at temperatures lower than 50 K. The aim is a BIB detector based on an integrated amplifier with the DePMOSFET as a promising candidate.

I. INTRODUCTION

The BIB detector represents an advancement of the common extrinsic photodetector in terms of higher quantum efficiency and broader wavelength response. Both detector types exploit the excitation of the electrons by infrared radiation from the shallow donor state (binding energy: 42 meV to 54 meV) into the conduction band. In comparison of extrinsic photodetectors, Si-BIB detectors are heavily doped (from $N_D = 10^{17}$ to $10^{18}$ cm$^{-3}$) to have a higher absorption coefficient [2]. The high n-doping of the BIB detector results in an impurity band which is a conducting band even at low temperatures. To prevent the leakage current from this impurity band a high-resistive epitaxial layer is grown on the high doped Silicon active layer. By applying a voltage $V_e$ the active layer is depleted over several microns. Only the excited electrons within the depleted width are driven by the electric field and can pass the blocking layer to the first readout node (figure 1). The aim is to introduce an integrated amplifier on the BIB detector as the first readout node for the signal electrons. To gain experience with such an amplifier at low temperatures down to 5 K, first steps are made on existing circular DePMOSFETs (figure 2).

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II. CHARACTERISTIC CURVES

We perform temperature dependent characteristic measurements from 5 K to 300 K. First results are shown in figure 3. The input characteristics show a threshold voltage shift up to -1.8 Volt at 5.8 K. Also, the slope is sharper with lower temperature showing the rise of the transconductance $g_m$. In the saturation regime the transconductance can be written as:

$$g_m(T) = \frac{\partial I_D}{\partial V_{GS}}|_{V_D=const.} \propto (V_{GS} - V_T) \cdot \mu_{eff}(T)$$

where $I_D$ is the Drain current, $V_{GS}$ is the Gate-Source voltage and $V_T$ is the threshold voltage. According to the above formula, the effective mobility is proportional to the transconductance at constant $V_{GS} - V_T$. In figure 4 the function is plotted against the temperature at $V_{GS} - V_T = 2V$. It shows, that the transconductance, and consequently the effective mobility, increases with decreasing temperature, which should be shown in an increase of the transistor current. But, we observe a higher current with higher temperature in the output characteristics (figure 3). This reflects the threshold voltage shift, because at a lower temperature a higher Gate-Source voltage is needed to form the inversion layer in the Source-Drain channel. We do not observe any low temperature effects such as kink effects [3], which would give rise to impact ionization. Between the source drain contact there is a shallow Bor implantation, which has a concentration of about $10^{17}$ cm$^{-2}$. At 5.8 K and in this concentration regime the scattering lifetime is dominated by impurity scattering. That is why the mobility is in the range of $100 - 500 \frac{cm^2}{Vs}$ [4], which is lower than the mobility of valence band holes in intrinsic silicon. The mean free path of the holes is low so that they cannot gain sufficient high energy to ionize core electrons.

III. DYNAMIC MEASUREMENTS

We performed dynamic measurements on a single pixel DePMOSFET, where we irradiate it with x-rays ($K_{\alpha}$-line: 5.9 keV) originating from the nuclear decay of $^{55}$Fe. Figure 5 shows the raw spectra of the $K_{\alpha}$- and $K_{\beta}$-line at room temperature and 6 Kelvin. The readout electronics, including frontend, filter and ADC, is outside the cryostat, while the DePMOSFET is mounted in the cryostat. The spectroscopic performance is limited in a way that the wiring from the chip to the first operation amplifier of the frontend is more than 1 m and has a capacitance of 220 pF. These long wires are made of stainless steel to prevent heat conduction from the outer cryostat to the chip.
The high background of these spectra can be explained by the small size of the single pixel. The cross-sectional area of the internal gate is 9 \( \mu m \times 6 \mu m \) which results in splitting of the signal charges into several neighbouring pixels. The current of the transistor is 54 \( \mu A \) which is the maximal applied current before the temperature of the temperature diodes increases. This would explain the reduced amplitude compared to room temperature. Under cryogenic conditions, the specific heat is reduced by four orders of magnitude resulting in a high increase in temperature at low power dissipation [6]. The band gap energy of silicon is increased from 1.12 eV to 1.19 eV at 6 Kelvin, which results in a higher value for the mid value to excite an electron-hole pair from 3.6 eV to 3.8 eV.

IV. THE CLEAR MECHANISM

The spectra shown in figure 5 are obtained by sampling before and after clearing the DePFET (Sample 1 and Sample 2 in figure 6) and perform correlated double sampling. At room temperature it is possible to clear the DePFET completely and the difference of sample 1 and sample 2 during the clear time is taken. The 1/f-noise and the reset noise can be reduced, when a complete clear is fulfilled.

At temperatures below 40 Kelvin it is not possible to clear the electrons from the internal gate with one clear pulse. A low fraction of the generated signal charge can be removed where several clear pulses are needed to empty the internal gate. For example, more than 1000 clear pulses at 30 K are needed to clear the internal gate completely (see figure 7). We observe that this behaviour is a strong function of the temperature. To obtain a spectrum we have to take the difference of the two samples during the collection time. This allows a clear independent measurement, but this method increases the 1/f-noise caused by the long time distance of the collection time (120\( \mu s \)) compared to the clear time (4.2\( \mu s \)).

The incoming signal charges are trapped in the shallow donor states of the internal gate. The recombination time is low because of the heavily doped high energetic implant of the internal gate. The recombination time \( \tau_r \) can be formulated as [8]:

\[
\tau_r = \frac{1}{A \times N_{\text{eff}}} 
\]
\[ \tau_r = \frac{1}{\sigma_n v_{th,n} N_D} \]

where \( \sigma_n \) is the capture cross section of the shallow donor states, \( v_{th,n} \) is the thermal velocity of the electrons in the conduction band and \( N_D \) is the doping concentration in the internal gate. It is assumed, that these shallow donors are all unoccupied. This assumption can be made, because the region under the Source-Drain channel of the DePFET is depleted and the donors are completely ionized. The internal gate has a doping concentration of \( N_D = 10^{16} \text{ cm}^{-3} \) and for the product of \( \sigma_n \cdot v_{th,n} \) we obtain \( 7 \cdot 10^{-6} \text{ cm} \text{ s}^{-1} \) [7]. With these values we obtain a recombination time of \( \tau_r = 1.4 \cdot 10^{-11} \text{ s} \). When a signal charge arrives at the internal gate within the integration time, the electrons are trapped.

The thermal energy is as low (\( k_B T = 0.42 \text{ meV at 5 Kelvin} \)) that a long time is required to excite the signal charges into the conduction band. The average time between electron capture and re-emission can be written as [8]:

\[ \tau = \frac{1}{\sigma_n v_{th,n} e^\left( \frac{E_d - E_i}{k_B T} \right)} \]

where \( E_d \) is the binding energy of the shallow donors of Phosphorous and is 45.7 meV, \( n_i \) is the intrinsic electron concentration, \( E_i \) is the intrinsic energy level. This function is plotted against the temperature (see figure 8). At temperatures below 40 K the electrons in the trapped shallow donor states do not have sufficient high thermal energy to be excited into the conduction band within a time constant of microseconds. The electrons which are emitted with a longer time constant
are trapped during the clear time and a sufficient high amount of sequences is needed to clear the electrons from the internal gate (see figure 7).

![Fig. 8. The average time between electron capture and re-emission in dependent of the temperature is plotted against the temperature. At temperatures lower than 40 Kelvin the emission time is in the range of microseconds and higher. Typical clear times at room temperature applications are in the range of several nano- to microseconds.]

V. CONCLUSION

The DePMOSFET is a promising candidate for a cryogenic integrated amplifier on a Si-BIB detector. We performed temperature dependent characteristic measurements. We did not observe any low temperature effects such as kink effects and hysteresis in the output characteristic. Also, we can take a spectrum at temperatures down to 6 Kelvin, which shows the same peak-to-background as at room temperature. The reduced amplitude can be explained by the lower transistor current. It is not possible to clear the electrons from the internal gate completely, when we operate the DePMOSFET like in room temperature applications [9]. We explain this phenomena with the freeze out of signal charges in the heavily doped internal gate. The characterization of the BIB detector in terms of the quantum efficiency is necessary before we develop a BIB detector combined with an integrated DePMOSFET.

REFERENCES