MOSFET

(Experiment #24)

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1. Which relationship has to be between ω, C_M and C_{probe} in order to be V_M direct proportional to C_{probe}?

As we used a capacitive voltage divider, we use the following equation:

$$\frac{V_M}{V_0} = \frac{C_M + C_{probe}}{C_M}$$

$$\Rightarrow \frac{V_M}{V_0} C_M - C_M = C_{probe}$$

$$\Rightarrow C_{probe} \approx C_M \cdot \frac{V_M}{V_0}$$

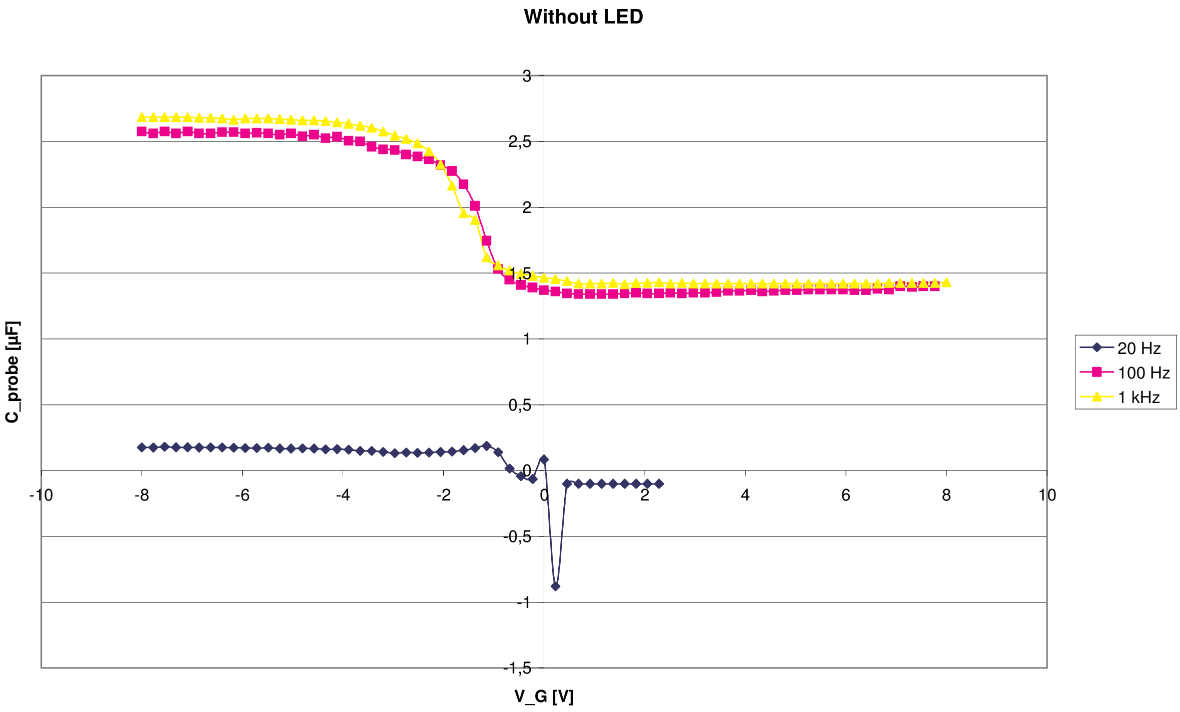
with

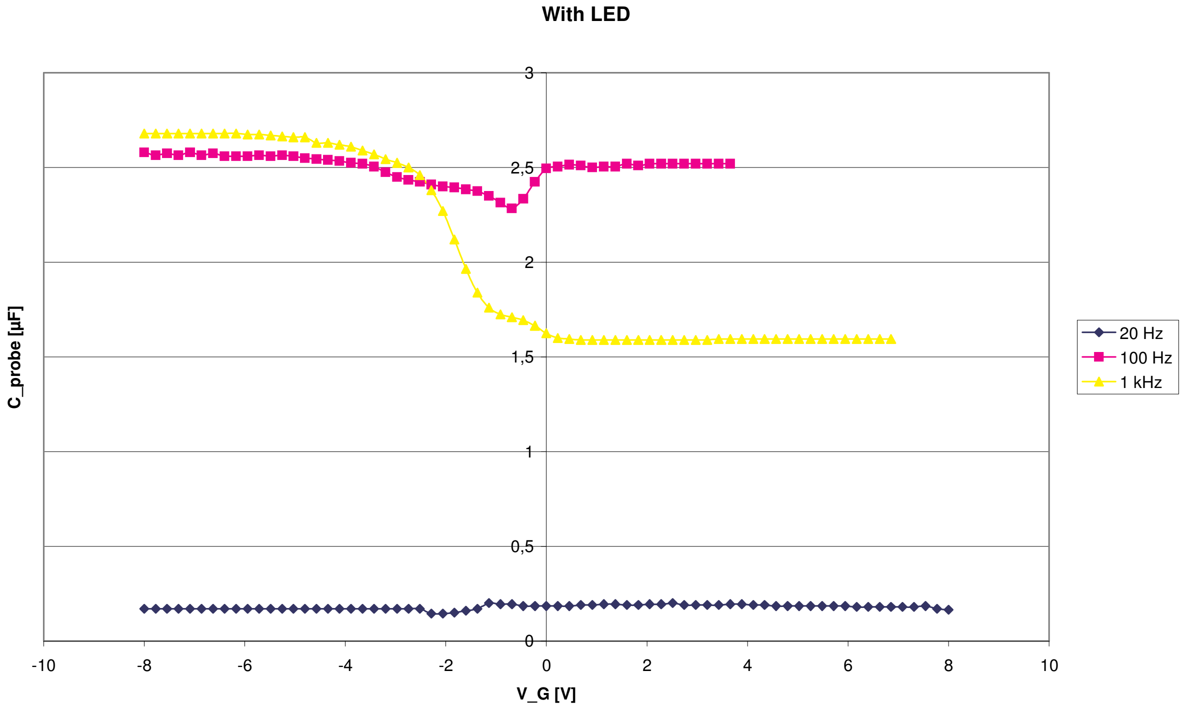
$C_M = 500\text{nF}$

$V_0 = 100\text{mV}$

2. Determine the kind of donators in the probe

As it is said in the script we changed the gate-voltage V_G and measured V_M, once using an LED and once without using an LED:





You can see in both diagrams that at higher (positive) voltage V_G the capacity is decreasing. Therefore our probe must have p-donators, because when V_G is positive more and more electrons come to the gate-contact and the capacity is decreasing. In conclusion current is transported by the holes and not by the electrons.

Another point one can see from the diagrams is that we don't have an ideal MOSFET. The bands of an ideal MOS-structure are flat at $V_G = 0\text{V}$, but here the highest capacity isn't reached yet, so there is not flat-band state at this point. The flat-band state nearly occurs at $V_{FB} \approx -4{,}6\text{V}$. With the help of this value we know the capacity of SiO_2 in the flat-band state $C_{SiO_2} = 500\text{nF} \cdot \frac{0{,}532\text{V}}{100\text{mV}} = 2{,}66\mu\text{F}$ and can calculate the thickness of the inversion layer (see 3.)

In the last diagram the curves are more different from each other than in the diagram above. The reason for this is that when we go to positive voltage an inversion layer is formed by the electrons. This can only happen when the applied frequency is not too high, so that the electrons can follow the changing electric field. At 100 Hz this is still possible and as a consequence the capacity increases again. When the LED is off this effect can't be seen, because there aren't enough electrons available to form the inversion layer.

3. Determination of the concentration of interface traps

With the lowest possible capacity $C_{\min} = 500\text{nF} \cdot \frac{0{,}284\text{V}}{100\text{mV}} = 1{,}42\mu\text{F}$ we can determine the thickness of he inversion layer:

$$d_{inv} = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{C_{inv}}$$

with

$$\varepsilon_0 = 8{,}85 \cdot 10^{-12} \frac{F}{m}$$
$$\varepsilon_r = 11{,}7$$
$$A = 10\text{mm}^2 = 1{,}0 \cdot 10^{-5}\,\text{m}^2$$

C_{inv} can be calculated by assuming that we have two conductors in series:

$$\frac{1}{C_{inv}} = \left(\frac{1}{C_{\min}} - \frac{1}{C_{SiO_2}} \right)$$

$$\Rightarrow d_{inv} = \varepsilon_0 \cdot \varepsilon_r \cdot A \cdot \left(\frac{1}{C_{\min}} - \frac{1}{C_{SiO_2}} \right)$$

$$\Rightarrow d_{inv} = 8{,}85 \cdot 10^{-12} \frac{\text{F}}{\text{m}} \cdot 11{,}7 \cdot 1{,}0 \cdot 10^{-5}\,\text{m}^2 \cdot \left(\frac{1}{1{,}42 \cdot 10^{-6}\,\text{F}} - \frac{1}{2{,}66 \cdot 10^{-6}\,\text{F}} \right)$$

$$\Rightarrow d_{inv} = 0{,}3\text{nm}$$

Therefore we know the volume where interface traps occur (V_{inv}). When we assume that at each interface trap we only have one electron the concentration of interface traps can be calculated like this:

$$\rho = \left| \frac{Q}{e \cdot V_{inv}} \right| = \left| \frac{Q}{e \cdot d_{inv} \cdot A} \right|$$

As the capacity C_{min} is nearly constant we can use the following equation to calculate Q:

$$Q = \int_{0V}^{8V} C_{\min}\, dV \approx C_{\min} \cdot 8\text{V}$$

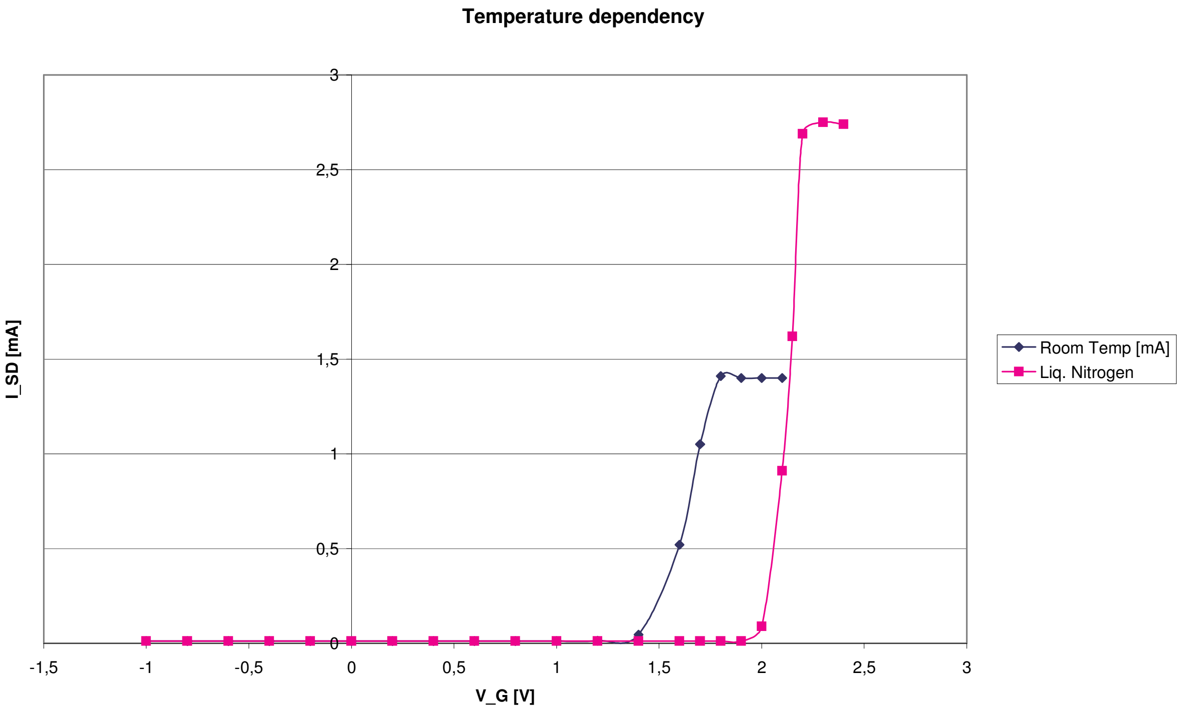
$$\Rightarrow \rho = \left| \frac{C_{\min} \cdot 8\text{V}}{e \cdot d_{inv} \cdot 1{,}0 \cdot 10^{-5}\,\text{m}^2} \right| = \left| \frac{1{,}42 \cdot 10^{-6}\, F \cdot 8\text{V}}{1{,}6 \cdot 10^{-19} \cdot 0{,}3 \cdot 10^{-9} \cdot 1{,}0 \cdot 10^{-5}\,\text{m}^2} \right| = 2{,}37 \cdot 10^{28} \frac{1}{\text{m}^3} = 2{,}37 \cdot 10^{22} \frac{1}{\text{cm}^3}$$

Additionally we can calculate the thickness of the isolating area, too:

$$d_{SiO\,2} = \frac{A \cdot \varepsilon_{SiO_2}}{C_{SiO_2}} = \frac{1{,}0 \cdot 10^{-5}\,\text{m}^2 \cdot 3{,}5 \cdot 10^{-11}\,\text{F/m}}{2{,}66 \cdot 10^{-6}\,\text{F}} = 1{,}3 \cdot 10^{-10}\,\text{m}$$

4. Temperature dependency of I_{SD}

We measured the temperature dependency of the Source-Drain-current I_{SD} at two temperatures: First we measured it at room temperature, then we cooled the MOSFET down to 77K with the help of liquid nitrogen.



Obviously V_T (= threshold voltage) decreases when you increase the temperature, but the maximum current is reached much faster. As we had some problems to adjust V_G properly[1], we can't tell, whether the sharp maximum current for temperature is correct, but we think generally it should look like this. At higher temperature there are more phonons and the ohmic resistance is probably also higher. Therefore you would expect that at higher temperature you have less maximum current.

From the diagram you get the following threshold voltages:
$V_T^{77K} \approx 2{,}0\text{V}$, $V_T^{300K} \approx 1{,}4\text{V}$

5. Calculating the effective mobility

By using the given equation form the script we can calculate the effective mobility:

$$\mu_{eff} = \frac{\frac{L}{W} \cdot \frac{I_{SD}}{V_D}}{\frac{C_{SiO_2}}{L \cdot W}(V_G - V_T)} = \frac{\frac{L}{W} \cdot \frac{I_{SD}}{V_D}}{\frac{\varepsilon_{SiO_2} \cdot A}{L \cdot W \cdot d}(V_G - V_T)} = \frac{\frac{L}{W} \cdot \frac{I_{SD}}{V_D}}{\frac{\varepsilon_{SiO_2}}{d}(V_G - V_T)}$$

with

the channel length L = 100nm
the channel width W = 100µm
the insulator thickness d = 15nm
the permetivity $\varepsilon_{SiO_2} = 3{,}5 \cdot 10^{-11}$ F/m

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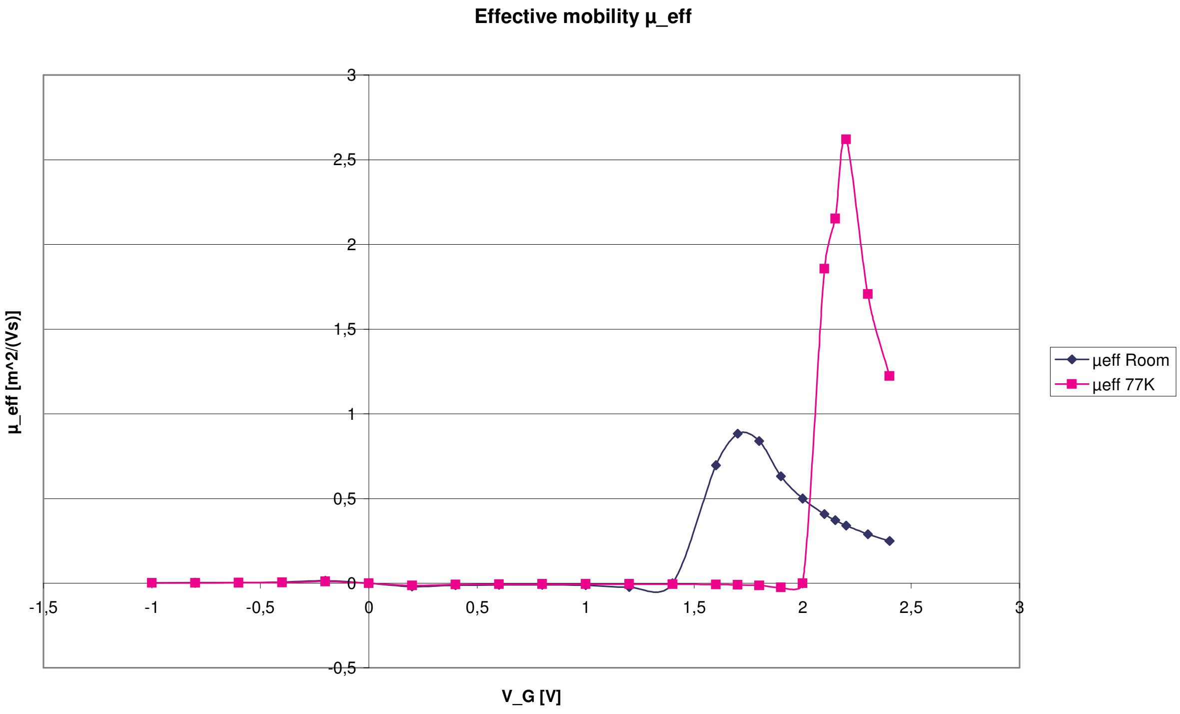
[1] The „real“ V_G often didn't do what we wanted it to do: When we increased it a little bit it sometimes jumped suddenly to a much higher level so that we probably crashed one MOSFET. The reason for this lies probably in the fact that the equipment is not the newest one...



We get:

77K: $\mu_{eff} = 2{,}62\,\frac{\mathrm{m}^2}{\mathrm{Vs}}$;

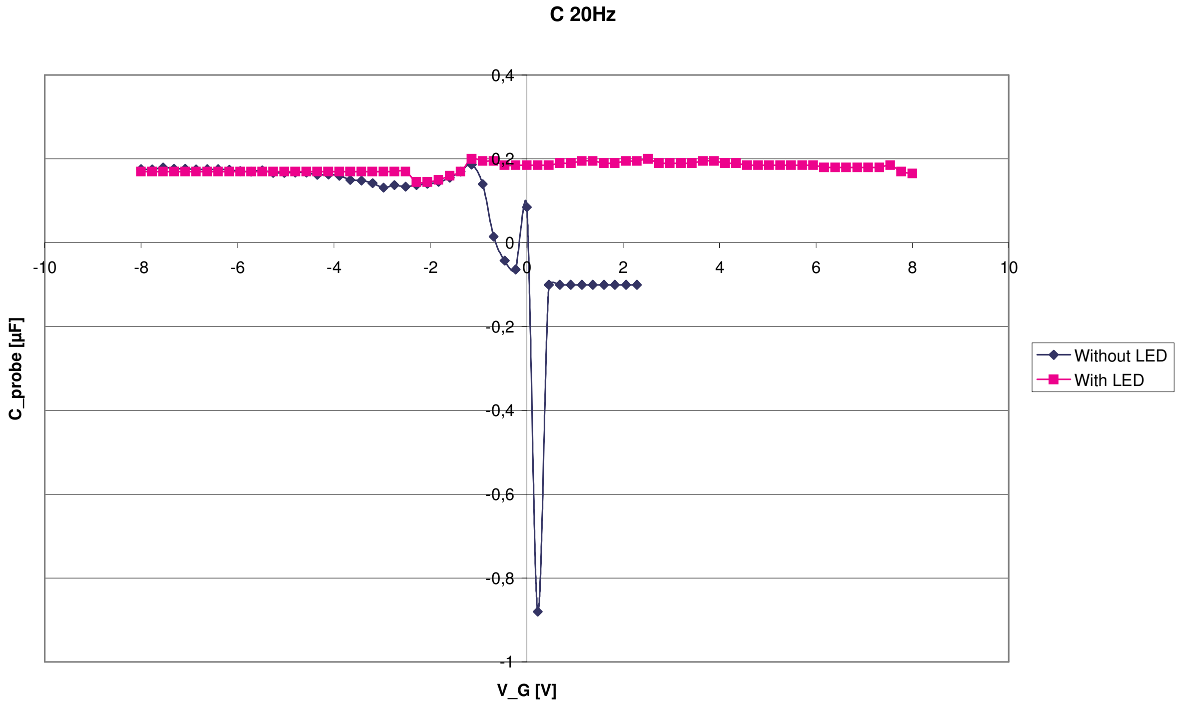
300K: $\mu_{eff} = 0{,}88\,\frac{\mathrm{m}^2}{\mathrm{Vs}}$

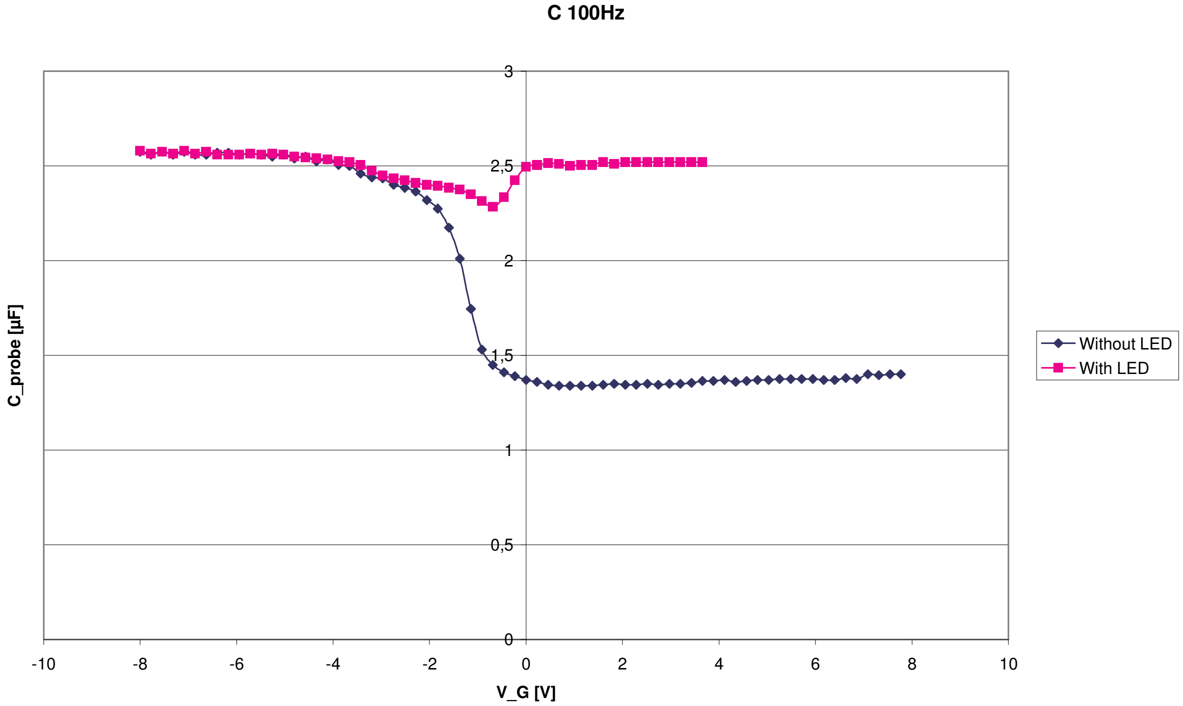
With this values we can calculate the mean-free time:

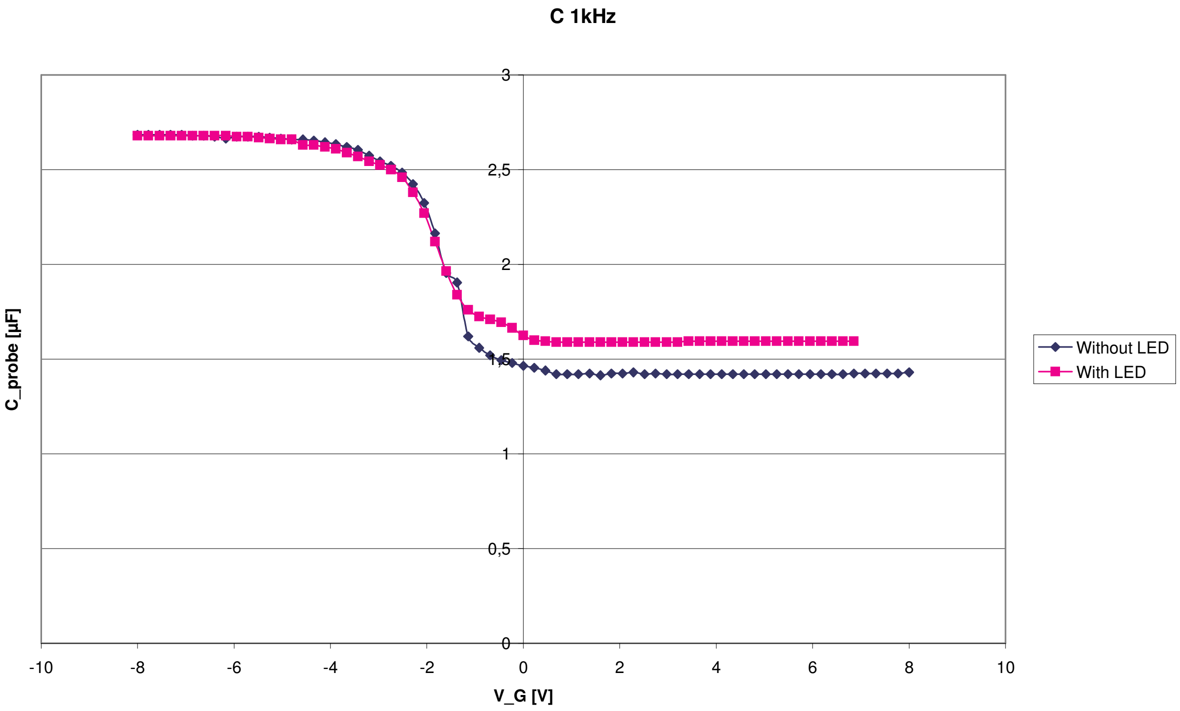
$$\tau = \mu \cdot \frac{m^*}{e} = 0{,}2 \cdot \mu \cdot \frac{m_e}{e}$$

77K: $\tau \approx 2{,}98\mathrm{ps}$;
300K: $\tau \approx 1{,}0\mathrm{ps}$

Finally we tried to measure I_{SD} depending on V_{SD} with a constant value V_G, but whenever we changed the range for I_{SD} at the measuring instrument the values changed a lot for the same V_{SD}. Therefore we are not able to tell anything about this dependency.


C 20Hz
0,4
0,2
0
-0,2
-0,4
-0,6
-0,8
-1
-10
-8
-6
-4
-2
0
2
4
6
8
10
C_probe [µF]
V_G [V]
Without LED
With LED


C 100Hz
3
2,5
2
1,5
1
0,5
0
-10
-8
-6
-4
-2
0
2
4
6
8
10
C_probe [µF]
V_G [V]
Without LED
With LED


C 1kHz
C_probe [µF]
V_G [V]
3
2,5
2
1,5
1
0,5
0
-10
-8
-6
-4
-2
0
2
4
6
8
10
Without LED
With LED