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Programmable Low Pass Filter Using the Gated Diode in Breakdown Collapse Regime

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Abstract. In this paper we present a unity-gain follower amplifier based on a gated diode operated in breakdown regime in common cathode configuration. The amplifier has only one stage and it provides power amplification, high input impedance and a low output one. The maximum frequency that can be applied on the entrance of the amplifier so that the output remains undistorted is dependent on the bias current therefore it can be used also as a programmable low pass filter. The diode is fully characterized in order to set the bias in the linear region where the amplification is very close to one.

Keywords: Gated Diode, Breakdown, Common Cathode, Small Signal.

1. Introduction

The gated diode operated in the breakdown regime presents a high interest due to the low power operation, sub-thermal switching speed and CMOS compatibility [1, 2]. The operation in the breakdown regime generated a new class of analog circuits that can operate at a very low power [3]. The operation of the diode in the breakdown mode, common cathode configuration, gives the advantage of having a quasi-linear transfer characteristic with a slope very close to one [1]. Exploring this regime, our main contribution in this paper is the design of a unity gain amplifier. Furthermore we measured the maximum frequency that can be applied at the entrance in order to obtain the output signal with minimum distortions. The amplifier is a one stage amplifier without any feedback, with high impedance given by the MOS gate and low output impedance given by the pn junction avalanche regime.

The cross section of the utilized device is presented in Fig. 1. It is a lateral junction fabricated in 3M2P_CMOS process with 128 Å as a gate oxide, the doping of the well being 2×10^{15} cm^{-3}. The flatband voltage is $V_{FB} = -0.1$ V and the area of the gate gives a gate capacitance of approximately 4 pF.

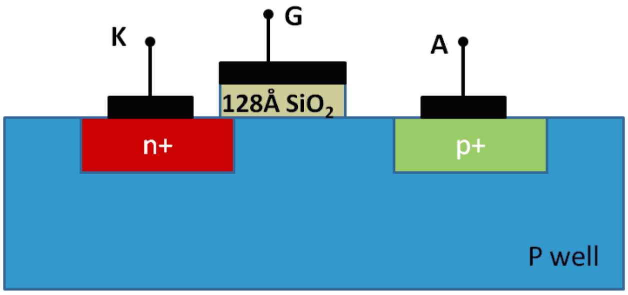

Fig. 1. Cross section of the gated diode. The device was fabricated in CMOS technology.

2. DC Measurements

In order to set the bias for the amplifier, several DC measurements were performed with the aid of Agilent 4156C semiconductor parameter analyzer.

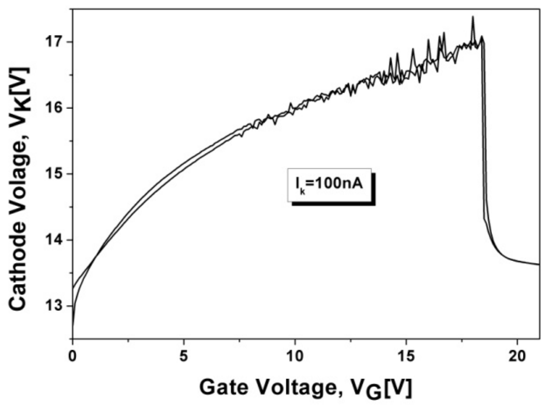

Fig. 2. The dependence of the breakdown voltage of the gated diode with respect to the gate voltage, in common anode configuration. I_k is the constant current bias of the *pn* junction.

Figure 2 presents the dependence of the gated diode breakdown voltage with respect to the gate voltage in common anode configuration from [1]. One can observe that at a certain voltage, the breakdown voltage drops very fast down, the diode entering in the collapse regime [4]. Another interesting observation is also a small hysteretic characteristic of 0.1 V. The exploration of the collapse region can be achieved if the diode is biased in the common cathode configuration [1] with a constant current I_A. The measurements are presented in Fig. 3:

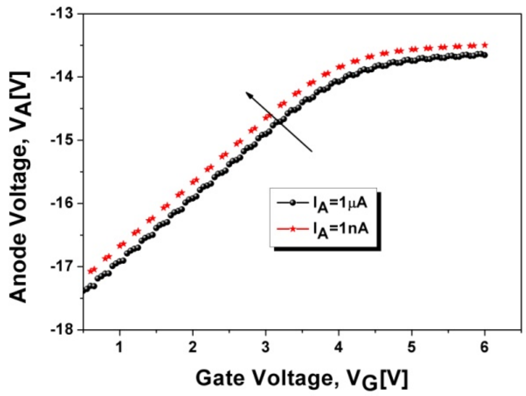

Fig. 3. The breakdown voltage depending on the gate voltage in the common cathode configuration.

In this configuration, the slope of the breakdown voltage with respect to the gate voltage is very close to one for a wide range of biases from 1 nA to 100 μA. In order to have minimum distortions we will bias the diode with a current in this range. The same constrains will be imposed for the gate voltage bias.

Figure 4 presents the derivative of the anode voltage with respect to the gate voltage, in common cathode configuration. Therefore the gate voltage that we will use to bias the amplifier will be around 2 V.

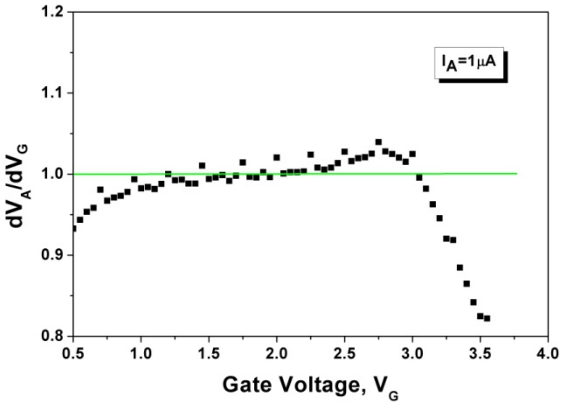

Fig. 4. Derivative of the anode voltage in breakdown regime with respect to the gate voltage, in common cathode configuration.

Subsequently, we measured the gate capacitance with a precision LCR meter, 4284 A. The anode and the cathode were grounded and the measuring signal was applied on the gate. Figure 5 shows the diode's gate capacitance with respect to the gate voltage based on the measurement methodology presented above.

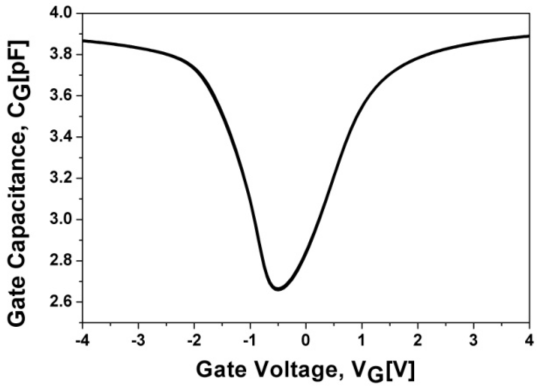

Fig. 5. The gate capacitance measured with LCR meter.

For further parameter extraction, the capacitance of the *pn* junction was measured leaving the gate floating; the result of the measurement is presented in Fig. 6.

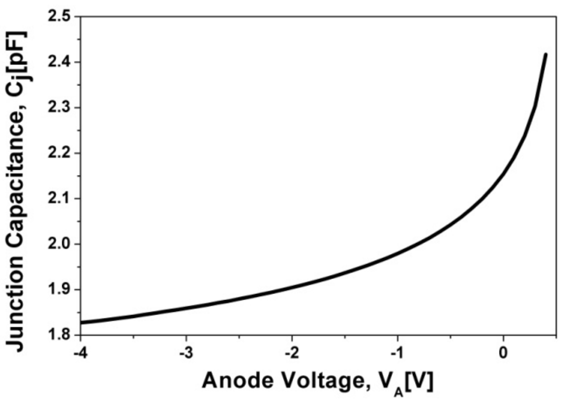

Fig. 6. The junction capacitance in reverse bias.

3. Unity gain amplifier

Using the unity gain of the diode's common cathode configuration we built a single stage, unity gain amplifier. The diode was biased with a constant current into breakdown regime, grounding the cathode, then applying on the gate a small AC signal superposed on a DC bias. The output signal was decoupled with a capacitor. Due to the fact that the bias current has small values, as small as 1 nA, the oscilloscope probe impendence was not high enough. As consequence, the voltage drop on the probe resistance was smaller than the breakdown voltage, therefore the diode was not entering the breakdown regime.

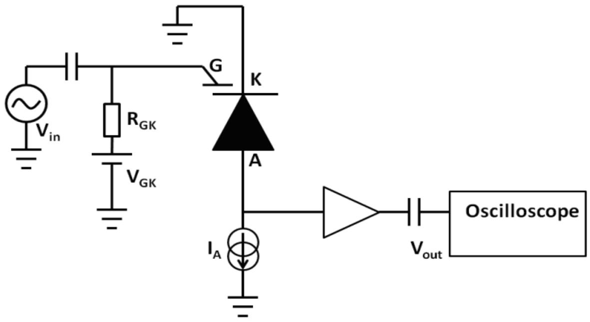

Fig. 7. Unity gain amplifier using the gated diode in common cathode configuration.

A high impedance buffer was utilized, having an impedance of 10 GΩ. The maximum frequency of the buffer was 4 MHz, therefore measurements over this frequency could not be performed. The measurement setup is presented in Fig. 7. The bias DC gate voltage positioned the diode in the linear regime, therefore the expected output voltage (V_{out}) will have the same value of the input voltage (V_{int}).

Figure 8 presents the input and the output voltage of the amplifier. The bias current was 100 μA and the amplitude of the input voltage was 100 mV at a frequency of 100 kHz.

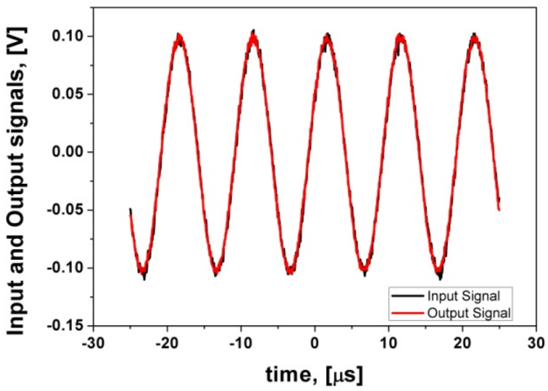

Fig. 8. The input and the output signal of the amplifier captured on the oscilloscope.

The DC bias of the gate was set to 2 V, a region where the slope of the breakdown voltage with respect to the gate voltage is very close to one, as it can be noticed in Fig. 4. By observing the shape of the signal on the oscilloscope, we could trace the curve for the maximum frequency, F_{MAX} that the amplifier can operate. Experimentally we observed that the maximum frequency depends on the bias current I_A. In Fig. 9 we report the dependence of the maximum frequency with respect to the bias current. The measurements were based only on human observation of the two signals on the oscilloscope therefore the points on the graph are subject to measurement errors. An interesting effect was observed when biasing the diode at 1 μA and at 3 μA (arrow in Fig. 9). Until 1 μA the maximum frequency was growing with the bias current but at 3 μA it drops from 10 kHz to 2 kHz. Several measurements on different diodes were performed and the effect can be observed at each diode. This effect should be further studied.

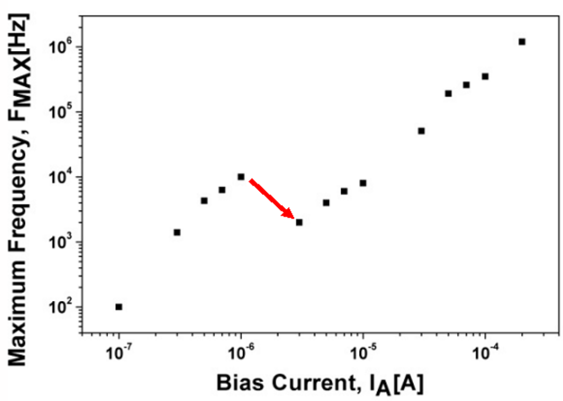

Fig. 9. The dependence of the maximum frequency applicable on the input of the amplifier with respect to the bias current.

After 3 μA bias current it can be observed that the maximum applicable frequency is growing with the bias current. 200 μA was the maximum current that could be applied for the output signal to have low distortions.

The dependence of the maximum frequency with respect to the bias current was extrapolated in the region with $I_A > 1$ μA and the dependence has the shape of a power function:

$$f_{\max} = 7 \cdot 10^{11} I_A^{1.5643}$$

Having calculated the dependence of the maximum frequency that the amplifier can operate with respect to the bias voltage a programmable low pass filter can be implemented utilizing the same circuit [5]. The frequency of the filter can be modified by changing the bias current.

One explanation for the dependence of the maximum frequency with the bias current is the amount of charge that the current supply can provide to the diode in order to change the voltage on the anode. The injected current has the definition of the amount of charge that passes thru a section in a certain time:

$$I = \frac{dQ}{dt},$$

where I is the current, Q is the charge and t is the amount of time that the measurement takes part.

The capacitance is defined as the charge at a certain voltage, therefore:

$$C = \frac{Q}{V} \rightarrow CV = Q \rightarrow C\frac{\partial V}{\partial t} = I,$$

$$\frac{\partial V}{\partial t} = \frac{I}{C},$$

where C is the capacitance and V is the voltage applied on the capacitor.

This formula shows that in order to apply a voltage variation on the gate and the anode voltage to follow it, the derivative of the applied signal should be less than the bias current over the capacitance of the diode in breakdown collapse regime. The applied voltage on the gate is $V = A\sin(2\pi\text{ft})$, where A is the amplitude of the sinusoidal voltage and f is the frequency of the signal. The derivative is $A2\pi f\cos(2\pi ft)$ and it reaches the maximum when the cosines is 1. Therefore the maximum voltage derivative of our applied signal is:

$$\left.\frac{\partial V}{\partial t}\right|_{MAX} = A2\pi f.$$

The condition for the maximum frequency that we can apply becomes:

$$f_{MAX} = \frac{I_{bias}}{C2A\pi}.$$

The capacitance of the gated diode in breakdown collapse regime could not be measured but in order to proof this theory a signal with the maximum frequency was applied on the gate. Maintaining the same bias current, the same current was applied but with different amplitudes. The result was presented in Fig. 10. The input signal was a 100 mV sinusoidal signal which frequency was modified at the limit that the amplitude of the output signal started decreasing (Fig. 10a). Afterwards, keeping the same frequency, the amplitude of the input signal raised at 200 mV and 300 mV (Fig. 10b and Fig. 10c). One can see that the time for the output signal to reach the same amplitude as the input signal is not sufficient therefore the amplitude of the output signal remains at a value close to the 100 mV, the amplitude that corresponds to the first signal applied. Another effect that one could observe is that the output signal is distorted when the voltage is descending. This comes again in the favor of our theory because in order to have a smaller voltage on the capacitor, charge must be added. The adding of charge on the capacitor when the voltage is decreasing is due to the fact that the voltage on the anode is negative.

Next, the bias voltage applied on the gate was modified and additional measurements were performed. As expected, the maximum frequency did not change if the diode was biased in the linear regime. The acceptable range for the bias on the gate was as expected 1.5 V to 3 V.

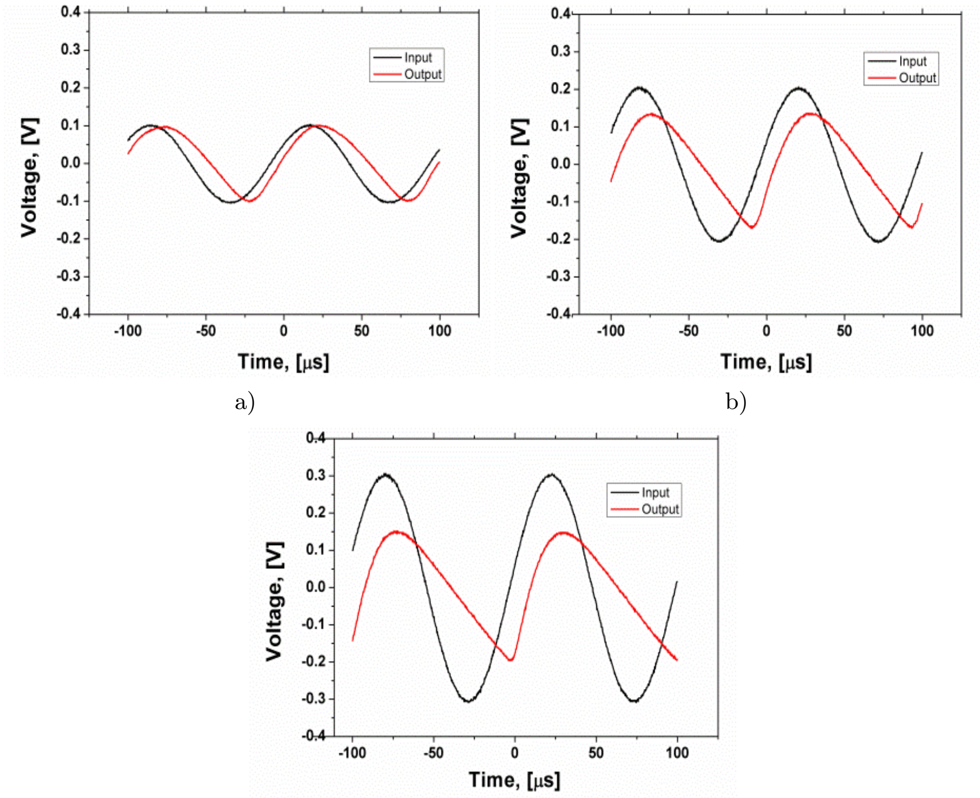

Fig. 10. Different amplitude signals applied on the gate of the gated diode.

4. Conclusions

In this paper we presented the full characterization of the gated diode operated in breakdown regime in both common anode and common cathode configuration as well as the small signal regime of a unity-gain amplifier in common cathode configuration. From measurements we extracted the dependence of the maximum frequency on the bias current. With the aid of this dependence a low pass filter with programmable threshold frequency was implemented and the theory behind the frequency dependence on the bias was proposed. A set of equation that will serve on designing a low pass filter with variable threshold was presented.

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