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GATE-CONTROLLED DIODE – A NEW WAY FOR ELECTRONIC CIRCUITS

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The paper presents new applications for the gate-controlled diode working in the breakdown regime. The proposed circuits are based on the special transfer characteristic having linear portions and switching with hysteresis features. Two examples are given, namely the follower amplifier and the relaxation oscillator.

1. INTRODUCTION

The gate-controlled diode (or gated diode) is a semiconductor device that combines the function of a ***p-n*** junction and a MOS capacitor [1, 2]. The schematic cross-section structure is shown in figure 1. The terminals of the junction are noted **A** (anode) and **K** (cathode), while the control electrode is the gate **G**. The voltage across the ***p-n*** junction working in avalanche breakdown regime has the absolute value V_{BR}**.** The control voltage, refereed to the anode, is V_G as is known in the common-anode configuration. Taking into account the electrical isolation of the gate, the currents through anode and cathode are equal, their value being noted I_R (see figure 2).

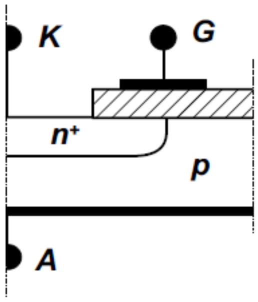

Fig. 1 – The schematic cross-section.

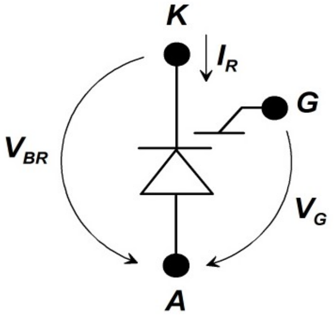

Fig. 2 – The symbol of the gate-controlled diode.

Initially, the gate-controlled diode was used as a test vehicle for the study of surface influence on the *p-n* junction electrical characteristics and inversion of the MOS capacitor in the presence of a *p-n* junction.

The avalanche breakdown regime of the gate-controlled diode was studied, also. The main results lie in the domain of the breakdown for the *p-n* junction, controlled by gate bias, and for the MOS capacitors in deep-depletion condition.

Recently, several semiconductor structures working in the breakdown regime were conceived in order to obtain slopes of the transfer characteristics greater than the slopes offered by the diffusion law. The first in this series has been the IMOS [3] that is a gate-controlled diode. With this application, the gate-controlled diode evolved out from the test-device class, becoming useful switching device.

2. BASIC PROPRETIES

An electronic circuit component performs the *active* function if it has a power amplification greater than unity [1]. The gated diode is characterised by a very high power amplification gain. Firstly, it can mention the MOS input command that doesn't consum power considering the gate currents very small. Secondly, the output is offered by a junction working in avalanche regime, where the currents are set at predetermned non-destructive values limited only by thermal conditions. The output voltages are externally provided by current-controlled voltage generators, at the breakdown voltages of the gate-controlled diodes. These values can be set in a large scale of values, by appropriate device design. In this way, the gated diode can be considered as having an unlimited power output. This is obtained by the requirement for the gated diode to be biased with a constant-current source, instead a constant-voltage source as is used in circuits with transistors. Considering the high input impedance and low output impedance, the gate-controlled diode acts as a *voltage-controlled voltage source*.

With the externally provided electronics for automatic biasing in breakdown condition, at specified diode reverse current, the gate-controlled diode, a non-amplifying device in itself, can thus be the key electronic device of an active circuit.

Another general performance is related to the speed of the electronic circuits. The gated diode, working in the avalanche regime, acts with **hot majority-carriers**. These carriers, generated and drived by high electric fields, acquire high speed/mobility. Supplementary, considering the reverse bias of the juncton, the electrons are collected by the n-region and the holes – by the p-region, respectively. Thus, the carriers recombination does not occur, with good influence on action speed. These are important for the liniar circuits that could work at very high frequencies without negative feedback procedures. As for the switching speed, at the onset of the breakdown voltage collapse, this is determined by the speed at which the avalanche current builds up. This avalanche breakdown process being regenerative, is expected to be much faster than the transit-time or recombination-limited switching processes of conventional devices. In adition, the switching is associated with hysterezis, which enables special applications.

3. COMMON-ANODE TRANSFER CHARACTERISTIC

The transfer characteristic represents the key element for electronic circuits design. The common-anode configuration in avalanche regime is directly linked with physical phenomena inside gated-controlled diode [2, 4]. The transfer characteristic means the dependence of the breakdown voltage ($\boldsymbol{V_{BR}}$) on the gate voltage ($\boldsymbol{V_G}$) for a constant reverse curent $\boldsymbol{I_R}$. A typical dependence is shown in figure 3. The breakdown voltage at $\boldsymbol{V_G}$ = 0 is noted $\boldsymbol{V_{R0}}$. In the both domains of voltages, positive and negative ones, a linear portion is

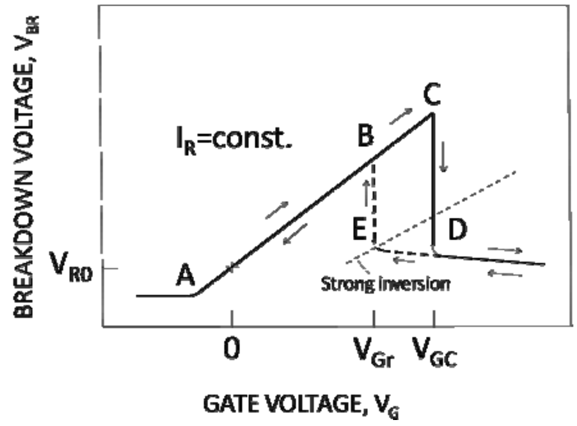

Fig. 3 – Common-anode transfer characteristic.

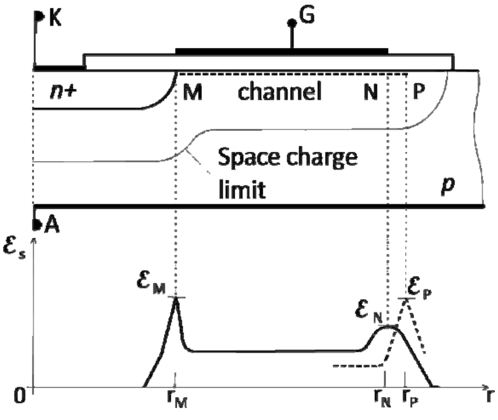

Fig. 4 – Qualitative surface electric field variation.

extended and is noted **A**-**B**-**C**. The slope of this stright line is m, lower but very close to the unity [5]; in this manner, its equation is:

$$V_{BR} = V_{R0} + m\, V_G \,. \qquad (1)$$

In the point **C**, a collapse of the breakdown voltage occurs, the portion **C**-**D** being practically a vertical line at the gate voltage V_{GC}. After the collapse, the breakdown voltage remains quasi-constant. Lowering the gate voltage, the characteristic has a hysterezis effect and returns to the linear portion in point **E (**line **E-B)**, at the voltage V_{Gr} ($V_{Gr} < V_{GC}$) [6].

The physical phenomena responsible of this behavior are shown in figure 4 [2, 5, 6]. In this figure it can observe the electric field at the surface ($\mathcal{E}_S$) along the radius r, from the junction to the outer edge of the gate. At these extremities, r_M and r_N, there are two peaks of the surface electric field, $\mathcal{E}_M$ and $\mathcal{E}_N$ respectively. In the linear portion **A**-**B**-**C**, the avalanche is located at the junction, the field $\mathcal{E}_M$ having its critical value. Increasing the gate voltage, the electric field inside the oxide, above the surface junction, must to be maintained constant because the critical field in silicon is essentially constant. As result, the breakdown voltage follows the gate voltage, resulting the linear characteristic **A**-**B**-**C**. At the gate voltage V_{GC}, the peak field $\mathcal{E}_N$ reaches the critical value and the avalanche is switched in the point **N**. The breakdown moves from the junction to the MOS capacitor that works in deep-depletion condition. The breakdown voltage of the structure V_{BR}, measured on cathode, drops rapidly to a small value, enough to collect the generated carriers (I_R); this switching in breakdown voltage is referred to as breakdown voltage collapse. This value is smaller than the minimum value of the reverse voltage that can sustain a deep depletion condition. As result, a channel appears at the semiconductor surface, below the gate. In this situation the peak of the electric field moves in point **P**, at the end of the channel (see the dashed line in figure 4). Due to very shallow induced junction (*n* channel- *p*) the critical field $\mathcal{E}_P$ is greater than $\mathcal{E}_N$ and, as a consequence, the breakdown voltage lowers additionally with respect to the MOS capacitor breakdown voltage.

The return to the linear variation, when the gate voltage decreases, is obtained by the re-establishing of the deep depletion condition as the gate voltage can no longer sustain the strong inversion condition at the new value of the reverse bias. This represents another switching condition than the one at the initial breakdown voltage *collapse*, to be referred as breakdown voltage *rise up*. Since the breakdown voltage rise up occurs at a lower voltage than the breakdown voltage collapse, a hysteresis breakdown voltage characteristic occurs. If the breakdown voltage collapse does not diminish the breakdown voltage bellow the threshold condition, the channel does not appear and the hysteresis feature is not present. Such a situation may be encountered for junctions with large series resistances and/or working at high reverse currents.

A comparison with other electron devices, the present transfer characteristic reveals a large domain of the trans-conductance values, from 1 (linear variation) to ∞ (collapse). In this manner, many circuits can be conceived, both analog and digital (switching). A special attention must be given to the instabilities of the characteristic generated by electrons injection in the oxide [7]. This behavior is specific for the avalanche regime and can be prevent by using special “electron transparent” oxides.

4. UNITY-GAIN FOLLOWER AMPLIFIER

The voltage amplifier with a unity gain is an electronic stage situated between a signal source with high internal resistance and a given, low-magnitude load. This circuit has a high input resistance and a low output one. In this manner, the amplifier requires less power from the signal source to drive the load than would be the case if the signal source were to drive the load directly. Or a signal with some internal resistance can now drive a load of comparable or even lower resistance without loss of amplitude (from the usual voltage-divider effect). In other words, this amplifier has currennt gain, even though it has no voltage gain; it has power gain [8].

The simplest unity-gain voltage amplifiers are made with a single transistor – emitter follower (bipolar) or source follower (field-effect). These stages have good performances, but are subjected to non-linearty and instabilities in raport with the bias and temperature. Better performancies can be achieved by using the negative feedback applied to operational amplifiers.

The gate-controlled diode has the best behavior in a single stage, without feedback. From beginning, the device is characterised by high input impedance, as the MOS gate-command get, and low output impedance, as the avalanche *p-n* junction assures. For this case, the linear portion of the transfer characteristic is used. The schematic of the unity gain follower amplifier is shwon in figure 5. The device is biased with the constant-current source $\mathbf{I_R}$. The operating point is established with the gate source $\mathbf{V_{G0}}$. The signal generator and the load are coupled via the capacitors $\mathbf{C_i}$ and $\mathbf{C_o}$, respectively. The dynamics of this schematic is shown in figure 6. The operating point $\mathbf{M_0}$ is situated in the middle of the **A**-**C** linear region in order to allow a maximum voltage amplitude of the input signal $\mathbf{V_i}$. As example, an amplitude of 75 V can be achieved [6], but is not a limit for special designed gate-diode. The current $\mathbf{I_R}$ is selected depending on the load resistor $\mathbf{R_L}$. The condition to maintain the breakdown regime during the load line sweeping is given by the equation:

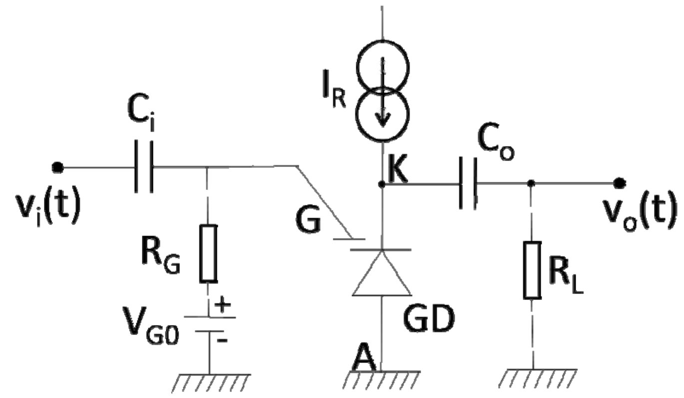

Fig. 5 – The schematic of the unity-gain follower amplifier.

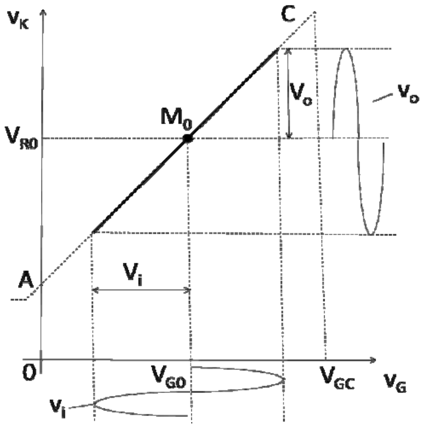

Fig. 6 – The load line of the follower amplifier.

$$\mathbf{I_R} \geq \mathbf{V_o} / \mathbf{R_L}, \tag{2}$$

where $\mathbf{V_o}$ is the amplitude of the output voltage ($\mathbf{V_o} \approx \mathbf{V_i}$). If the amplitude of the signal does not represent a restriction, the operating point can be situated at the $\mathbf{V_G} = 0$. In this situation, the resistance $\mathbf{R_G}$, the source $\mathbf{V_{G0}}$ and the capacitor $\mathbf{C_i}$ can miss so that the circuit offers the maximum input impedance.

In conclusion, this unity-gain follower amplifier can be recommanded as a power stage. Taking into account the hot majority-carriers action, it is a high frequency amplifier. All these performancies are obtained with the simplest schematic.

5. RELAXATION OSCILLATOR

The relaxation oscillator is made by alternate charging and discharging a capacitor through a resistor (or a current source). The switching between these two capacitor actions occurs when its voltage reaches some thresholds. The simplest schematic is based on a single negative-resistance device, such as unijunction transistor, but other solutions, more performing, use operational amplifiers or special timer integrated circuits.

The proposed relaxation oscillator, equipped with gated diode, is made on a schematic shown in figure 7. The gated diode **GD** has a bias obtained with the constant-current source $\mathbf{I_R}$. The capacitor **C** is charged with a constant-current source **I**. The diode **D** allows the switching of the capacitor between the two states, *charging* and *discharging*. The capacitor discharging is made through the diode internal resistance and the (low) output resistance of the gated diode. The resistor **R** can miss; otherwise, its presence allows the increase of the discharging period. The thresholds of this circuit are offered by the transfer characteristic of the gated diode, shown in figure 8, in a simplified form. The two thresholds of the gate voltage are $\mathbf{V_{GC}}$, corresponding to the collapse transition **1 – 2**, and $\mathbf{V_{Gr}}$, corresponding to the rise-up transition **3 – 4,** toward linear portion regime.

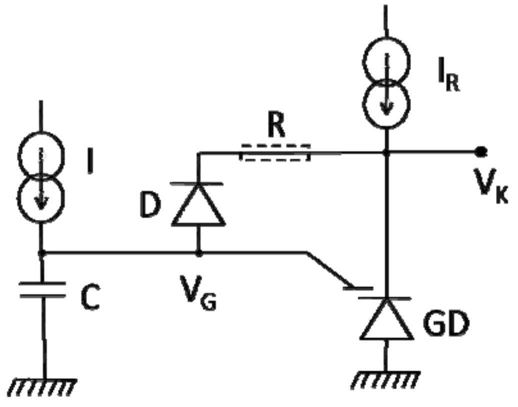

Fig. 7 – Schematic of the relaxation oscillator with gated diode.

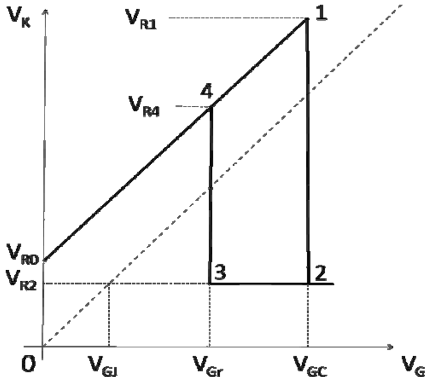

Fig. 8 – The simplified transfer characteristic.

The operation of the relaxation oscillator is synthesized in the time dependence of the gate and cathode voltages, as there are shown in figure 9. The gate voltage has a linear increase variation due the capacitor charging through the constant current, **I**. During this period, noted $\mathbf{T_1}$, the diode **D** is blocked considering its cathode voltage (breakdown voltage of **GD**) greater than anode one (gate voltage of **GD**), as is stated in equation (1). When the gate voltage reaches the threshold $\mathbf{V_{GC}}$, the cathode voltage decreases to $\mathbf{V_{R2}}$ value and opens the diode **D**. As consequence, the capacitor **C** is discharging through the circuit shown in figure 10. The inferior asymptotic limit of the gate voltage is noted $\mathbf{V_{GJ}}$ and is given by:

$$\mathbf{V_{GJ}} = \mathbf{V_{R2}} + \mathbf{R\,I}. \tag{3}$$

The voltage $\mathbf{V_{GJ}}$ must be lower than the threshold $\mathbf{V_{Gr}}$; this condition limits the upper value of **R**. If the resistor **R** misses, its value in equation (3) is replaced with the equivalent resistance R_i, given by:

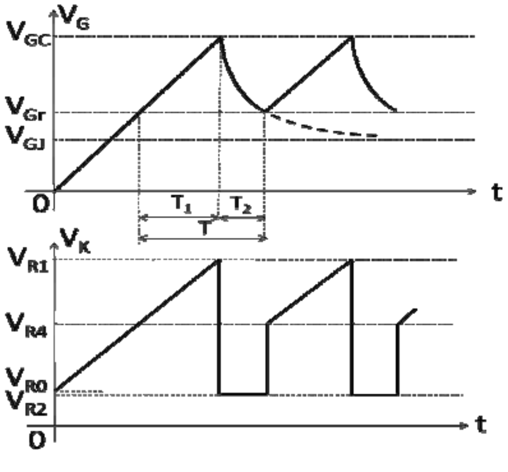

Fig. 9 – Time dependence of the gate and cathode voltages.

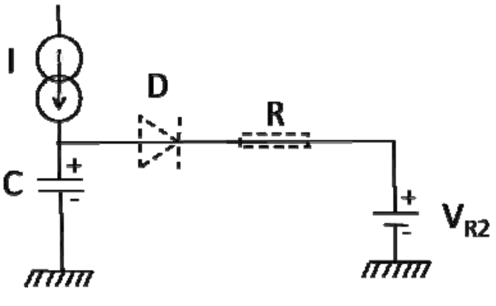

Fig. 10 – The equivalent circuit of capacitor discharging.

$$R_i = R_D + R_o, \tag{4}$$

where R_D is the internal resistance of the diode and R_o is the output resistance of the **GD** (dynamic resistance of the avalanche process). These both resistances have very small values so that $\mathbf{V_{GJ}} \approx \mathbf{V_{R2}}$ (see Fig. 8).

The period of the oscillator T is the sum between charging period (T_1) and discharging period (T_2) given by the equations:

$$T_1 = \mathbf{C}\,(\mathbf{V_{GC}} - \mathbf{V_{Gr}})/\mathbf{I}; \tag{5}$$

$$T_2 = \mathbf{C}\,(\mathbf{R} + R_i)\,\ln\,[(\mathbf{V_{GC}} - \mathbf{V_{GJ}}) / (\mathbf{V_{Gr}} - \mathbf{V_{GJ}})]. \tag{6}$$

The frequency stability is depending on the stability of the thresholds $\mathbf{V_{GC}}$ and $\mathbf{V_{Gr}}$; a good improvement is obtained by reducing the effects generated by the electron injection in the oxide [7]. Taking into account the gated diode performances, this relaxation oscillator is recommended for saw-tooth voltage generation (**R** = 0) in the domain of high power.

6. CONCLUSIONS

The paper revealed some performances of the gated diode working in the avalanche regime, in order to be a useful device in electronic circuits. The main features of such operation regime are the high speed action and the high power amplification. The transfer characteristic has large portions with linear shape combined with very sharp switching regions. Two examples of circuits are given, a unity-gain follower amplifier and a relaxation oscillator. The qualities of these circuits are obtained in the frame of the simplest schematics.

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