THE METAL-INSULATOR-SEMICONDUCTOR SWITCH (MISS), A NOVEL BISTABLE DEVICE

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I. Introduction

In the early seventies Yamamoto [1, 2] found an interesting phenomenon during the investigation of MIS structures. In the case of very thin (30...50 Å) insulating layers and in the occurrence of a $p-n$ junction near the layer the device showed a characteristic with negative differential resistance. Similar reports were given by Kroger and Wagener [3, 4, 5], then later by Simmons [6, 7] and Buxo [8]. The physical background remained obscure for a while, the first approximate model was given by Simmons [6], with some contradictions. Later he gave an exacter theory [7].

A new model, comprising the amplifying mechanism of the MIS diode (described by Green and Shewchun [10]) consists of two active devices [9] and explains some phenomena missing from the previous models. The MISS functioned in the case of different insulators, such as silicon dioxide, silicon nitride, polysilicon and recently also with tin dioxide [11].

The operation of the device

The structure of the device is shown in Fig. 1. It consists of a metal electrode (mostly aluminium), a thin (30...50 Å) insulating layer or a thicker (1000 – 2000 Å) polysilicon layer, one n-type layer and one heavily doped p-type (p^+) layer. Connecting a negative voltage to the metal and a positive one to the layer p^+, one gets the characteristics shown in Fig. 2. This characteristic is very similar to the characteristic of the $p^+-n-p-n^+$ (Shockley) diode, and has three regions with a high, a negative, a low impedance, respectively. Increasing the voltage upon the device from zero, a depletion layer forms at the insulator-semiconductor interface. Because the insulator is very thin, the holes, generated in the depletion layer, travel through it by tunneling, thus no inversion layer forms at the interface, which happens in the case of thicker insulators. This current is very low, but the voltage drop in the depletion layer may be quite high. Increasing the voltage increases the width of the depletion layer, thus the generation current increases, too. The current flowing across the device is, however, significantly larger than the current given by Simmons, which was the generation current. The electrons generated in the depletion layer enter the neutral part of the layer n, biasing the $p^+ - n$ junction into the forward direction, which in turn injects holes to the layer n. These holes diffuse to the depletion layer of the insulator-semiconductor interface, pass through the insulator and are collected by the metal. Thus the $p^+ - n$ part of the device (plus the insulator-semiconductor interface) creates a transistor effect with a current gain factor α_1. The actual current is:

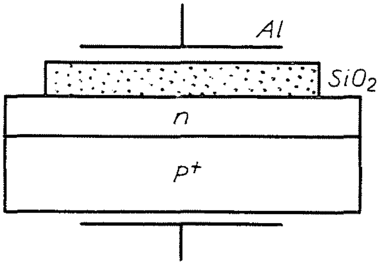

Fig. 1. Schematic structure of the MISS

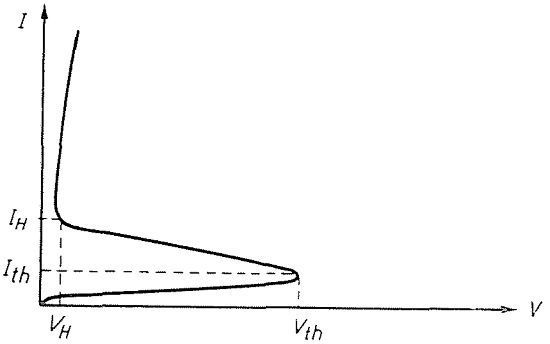

Fig. 2. Typical $I-V$ characteristics of the MISS.
V_{th}-threshold voltage: I_{th}-threshold current: V_H-holding voltage: I_H-holding current

$$I = \frac{I_g}{1-\alpha_1} \tag{1}$$

where I_g is the generation current.

Increasing the voltage, the depletion layer approaches the layer p^+ and the neutral part of layer n decreases. As a result both the efficiency of the p^+n junction and the transport factor increases, thus α_1 in (1) increases and I

increases significantly faster than does I_g. Near to the punch-through (but always at lower voltages) the current increases so much, that all the holes cannot pass through the insulator, they accumulate at the insulator-semiconductor interface. As a result, the field strength in the insulator increases, the metal starts to inject electrons into the semiconductor, these electrons bias the junction $p^+ - n$ even more into the forward direction, which in turn injects more holes, etc. Thus a positive feedback is created and the device switches to the low-impedance state.

The relation of the electron current injected by the metal to the whole current can be considered as the current amplification factor of the MIS diode and can be designated as α_2. The MIS diode thus behaves as another active element. The value of α_2 depends upon the shape of the potential barrier (for holes and electrons) of the MIS diode. The total current across the MIS diode can be controlled by the hole current, very similarly to the base current of a transistor. Increasing the hole current, at a certain voltage the inversion charge, and thus the field-strength in the insulator increases, which also increases the injected electron current and the hole current passing through the insulator. Finally an equilibrium state is achieved, when the hole current arriving to the interface is equal to that passing through the insulator. The equilibrium electron current is larger than the electron current was before the increase of the hole current.

The current passing through the layer n is the sum of the two injected currents and the generation current:

$$I = \alpha_1 I + \alpha_2 I + I_g \tag{2}$$

expressing I:

$$I = \frac{I_g}{1 - (\alpha_1 + \alpha_2)}. \tag{3}$$

Eq. (3) is the same as the one used for the Shockley diode. For $\alpha_1 + \alpha_2 > 1$ the device will be in the low-impedance state. The bipolar transistor gets into saturation, thus in the central layer n great many of holes and electrons accumulate. This causes charge-storage effects. If the time interval between two switch-in pulses is little, the threshold voltage decreases [12] and the turn-on time will be shorter. Preparing a contact to the layer n a three-terminal device can be constructed. With the aid of this electrode the junction $p^+ - n$ can be biased into the forward direction making it to inject holes, thus the inversion layer can be formed without reaching the threshold voltage and the device switches to the low impedance state, very similarly to a thyristor.

Turn-on condition for the avalanche-mode device

The operation of the device described above is based upon the punch-through. However, as shown by SIMMONS [6], there is another possibility to get a functioning MISS, namely by using the avalanche breakdown in the depletion layer of the insulator-semiconductor interface. This occurs at higher doping levels in the layer *n*, when the breakdown voltage is lower than the punch-through voltage. According to Simmons, the threshold voltage in this case is equal to the breakdown voltage. The experimental results, however, give always lower values than the breakdown voltage. Although this fact can partly be attributed to the junction-curvature effect at the side of the metal, there is another physical reason, which will shortly be explained in the followings, illustrated by Fig. 3.

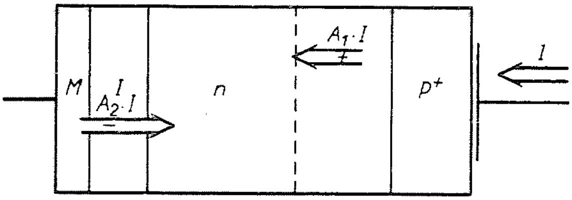

Fig. 3. Currents in the breakdown-mode MISS

Let x be the distance measured from the insulator-semiconductor interface and $x=W_i$ the boundary of the depletion layer. The electron current, entering into the depletion layer at $x=0$ is:

$$I_n(0)=I\alpha_2 \tag{4}$$

and the hole current, entering at $x=W_i$ into the depletion layer:

$$I_p(W_i)=\alpha_1 I \tag{5}$$

where I is the total current. If there is avalanche multiplication in the depletion layer, the total current can be expressed as [13]

$$I=\frac{I_n(0)+I_p(W_i)+\int\limits_0^{W_i} g\,\mathrm{d}x}{1-\int\limits_0^{W_i}\alpha\cdot\mathrm{d}x}=M\left[I_n(0)+I_p(W_i)+I_g\right] \tag{6}$$

where g is the generation rate of carriers, I_g is the total generation current in the depletion layer, α is the avalanche multiplication factor for holes and electrons (for the sake of simplicity taken to equal each other), and M is the multiplication factor, which depends upon the voltage as:

$$M=\frac{1}{1-\left(\frac{U}{U_B}\right)^n} \tag{7}$$

where U_B is the breakdown voltage and n is a constant. From Eqs (4. . . 7) one can express the current

$$I=\frac{I_g}{1-\left(\frac{U}{U_B}\right)^n-(\alpha_1+\alpha_2)}\,. \tag{8}$$

If the denominator of Eq. (8) becomes zero the device switches on, that is the threshold voltage is:

$$U_{\mathrm{th}}=U_B\sqrt[n]{(1-(\alpha_1+\alpha_2)} \tag{9}$$

Eq. (9) is a well-known relation for thyristors, but as seen, after defining α_2 it can be applied for the MISS, too. However, Eq. (9) does not suit to design the threshold voltage neither of the thyristors, nor of the MISS, because α_1, α_2 depend upon the current which in turn is related to the voltage. On the other hand, this formula points out that the threshold voltage is always lower than the breakdown voltage.

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Summary

The characteristics of the MISS can be explained by the intercoupling of two active devices. The model presented gives an "off"-state current larger than the generation current and a threshold voltage lower than the punch-through or the breakdown voltage of the bipolar part of the device. In the "on" state some charge-storage phenomena are expected.

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