RESEARCH OF TUNNEL-OXIDE AND BULK-BARRIER NEW ACTIVE DEVICES

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Received January 13, 1988
Presented by Prof. Dr. Tarnay

Abstract

A survey is given on the research activity and results concerning some new devices with thin (tunnel) oxide or bulk — barrier structure. This comprises experimental and theoretical works on the switching process on the MISS device. A new theory is given for the I—V characteristics of the MISS. Some new phenomena connected to the MISS are also reported. Beside the MISS, experimental results on the MIS emitter transistor (MISET) and on the tunnel — gateoxide MOS FET are discussed. A general scheme for amplifying and negative-resistance devices is given and some new devices are suggested.

At the Department of Electronic Devices a research work has been going on for about 8 years, aimed at the investigation of the physical operation of a family of new devices. In these devices a very thin oxide layer, where tunnelling of charge carriers takes place, plays a decisive role. This oxide together with a metal layer and the (usually *n*-type) semiconductor substrate form a tunnel MIS diode, which (at negative voltage on the metal) shows a current amplifying mechanism, [1] the holes arriving to the oxide-semiconductor interface form an inversion layer, as a consequence the field in the oxide increases which leads to an increase of the electron tunnel current.

In forward bias the tunnel MIS diode behaves similarly to a pn junction, especially, if the oxide thickness is under 2 nm. The ratio of the electron and hole tunnel currents is determined mostly by the metal work function. The lower is the metal work function, the higher is the ratio of the electron tunnel current to the hole tunnel current.

If the reverse biased tunnel MIS diode is connected to a forward biased pn junction, a negative resistance switching device, the MISS is constructed, as shown in Fig. 1. This device was first reported by Yamamoto and later widely discussed in the literature [2]. In the device an internal feedback takes place. The forward biased pn junction injects holes to the oxide-semiconductor interface, increasing the inversion layer charge there. This in turn increases the field strength in the oxide, leading to a higher electron tunnel current across it. These electrons arrive to the pn junction biasing it more into forward direction, which in turn injects more holes etc. Thus a positive feedback loop is formed. If the loop gain of this feedback loop reaches

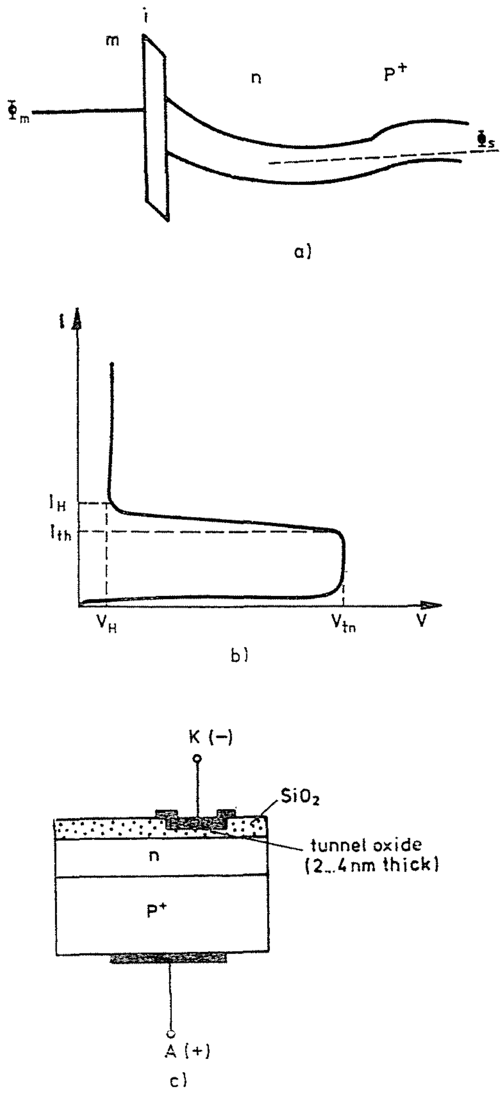

Fig. 1. Band diagram a) I—V characteristics (b) and structure (c) of the MISS

unity, the device switches to the low impedance state, where a low voltage drops upon the device at high currents. The existence of this feedback was discussed in [3], where in the so-called two-active device model the MISS was treated as the combination of a bipolar transistor and an amplifying tunnel MIS diode. In the on-state this transistor is in saturation, and beside it there is a high inversion charge at the oxide-semiconductor interface. At switching regime these charges cause some charge storage effects, decreasing the turn-on time of the device [4]. The switching transient of the

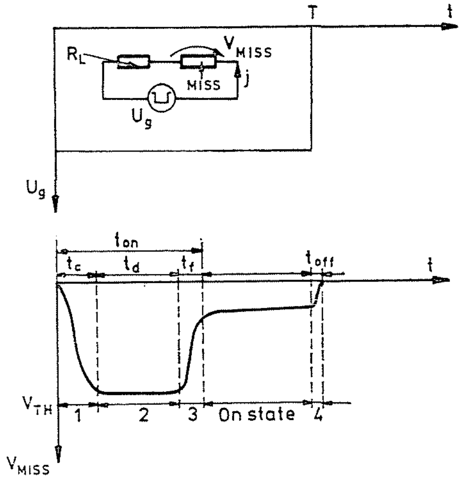

Fig. 2. Switching waveform of the MISS

device was also measured and analyzed [5]. The turn-on time comprises two phases (Fig. 2). In the first phase the accumulation of the inversion layer takes place, and the voltage upon the device is near to the static threshold (switchover) voltage. This phase can highly be reduced by increasing the supply voltage. In the second phase the regenerative process starts and a rather quick transition to a low voltage condition takes place. The length of this second phase is fairly independent from the supply voltage. The switch-on process is accelerated by illuminating the device [6]. In the switch-off process also a charge-storage effect can be observed, if during the switch-off the supply voltage has a forward direction, but the current flowing through the device is lower than the holding current (the minimum current in the low-impedance state). [7]

Preparing an ohmic contact to the n-layer (gate), the pn junction can be biased independently into forward direction, resulting in the decrease of the threshold voltage. This device is the MIST (MIS thyristor). Like in a thyristor, the MIST can be switched to the low impedance state by a current applied to the gate. The transient switch-on process initiated by the gate was also investegated [8]. The process also consists of two phases. In the first phase the diffusion charge in the base of the bipolar transistor part of the MISS is built up, like in a normal bipolar transistor. The „collector” current of this transistor then starts to build up the inversion charge at the oxide-semiconductor interface. If this charge reaches the critical value, the first phase ends and the regenerative switch-on process (second phase) starts, which is similar to the one of the MISS transient.

The difference of the areas of the tunnel oxide and the pn junction gives rise to two-dimensional effects, resulting in the change of the value of the threshold voltage. This was shown experimentally applying trench [9] or diffusion [10] isolation.

Some MISS devices displayed a negative resistence not only in the forward, but also in the reverse direction [11].

The first quantitative theory of the device was given by Habib [12]. This theory was extended incorporating into it the generation current in the surface depletion layer as well as some two-dimensional effects, the effect of surface states and inhomogeneous oxide thickness [13, 14]. As a result of the carrier generation in the surface depletion layer, the threshold voltage decreases sharply with temperature after reaching a critical temperature. Below that temperature the threshold voltage is practically constant. This critical temperature decreases with increasing oxide thickness (in the 1.5—4 nm range).

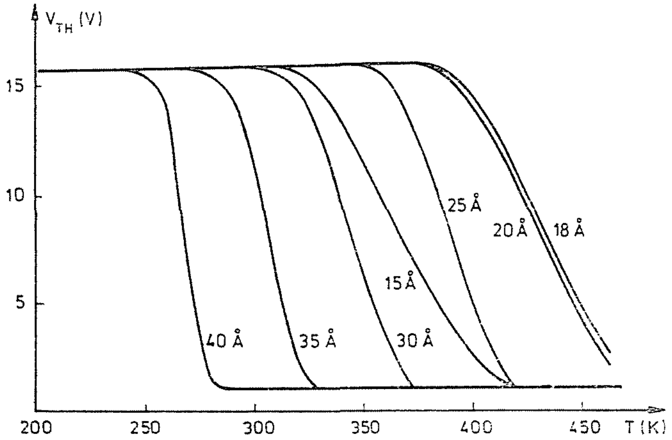

Fig. 3. Threshold voltage (V_{th}) versus tempreature of the MISS at different tunnel oxide thicknesses

The pin-holes and the surface states reduce the feedback loop gain in the device, thus increase the holding current.

The theory of MISS was farther developed, incorporating the avalanche multiplication at the oxide-semiconductor interface and the punch-through effects [15, 16, 17]. At low doping concentrations of the n layer the punch-through, at high doping concentrations the avalanche breakdown limits the threshold voltage. Thus with increasing doping concentrations the threshold voltage at low doping concentrations first increases, at medium doping concentrations reaches a maximum value, then starts to decrease as a consequence of the avalanche breakdown (Fig. 4). The temperature behaviour is also different in these two regions. In the punch-through region it was shown already in Fig. 3. In the avalanche region the threshold voltage decreases slowly with temperature. These two different temperature dependences were experimentally measured and reported [18].

Besides the MISS, other thin oxide devices were investigated, too. The minority carrier injection properties of the forward biased MIS tunnel diode can be used to create a bipolar transistor, where the emitter-base junction is formed not by the usual np junction but by a tunnel MIS diode. The advantage of this device is its simple structure, as it contains only one pn junction. The first short report of this device

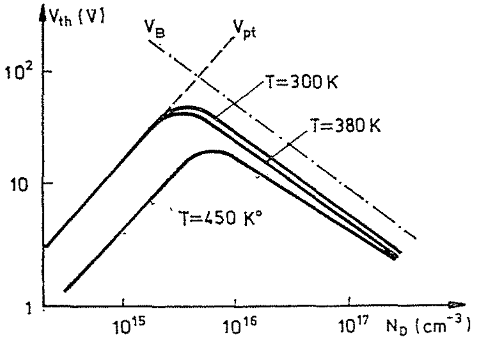

Fig. 4. Threshold voltage versus doping concentration of the MISS at different temperatures $d_{ox}=2$ nm

was given by Kishaki [19]. In [20] the results of the experimental work on this device are given. The highest current amplifications (between 50- and 70) were obtained at oxide thicknesses below 2 nm. In some cases, if the surface doping concentration of the base was rather low, a current jump could be observed in the collector current. This was explained by the formation of a parasitic MISS device.

If the collector is also replaced by a reverse-biased MIS tunnel structure, then a new structure called SOT (Surface Oxide Transistor), with a bipolar-transistor I—V characteristics is resulted. This device was first reported by Shewchun [21]. In this device at the collector, as it is a reverse biased MIS diode, a current amplification takes place which is connected to the formation of an inversion layer. In [22, 23] a voltage-controlled negative resistance in the SOT was reported. Increasing the collector voltage, after reaching a critical voltage, the collector current started to decrease. This phenomenon could be explained by the disappearance of the inversion layer and thus the amplifying mechanism at the collector.

With the decrease of the dimensions of the normal MOS FETS, the thickness of the gate oxide also decreases. Below 10 nm the tunnel currents flowing through the gate oxide must also be considered, resulting in a finite gate current and in the distortion of the drain current. P-channel FETs were fabricated, with gate oxides between 2 nm and 10 nm, and the I_G-V_{GS} and I_D-V_{DS} characteristics were measured [24]. A theory of the MOS FET, taking into account these tunnel currents, was also presented [25].

Some research was also done on the bulk-barrier diode. These are pnp or npn structures, where the central layer is a very thin one, thus it is completely depleted even at zero external bias, and a barrier is formed. If the doping concentrations in the exernal layers are very different, a diode-like assymetrical $I-V$ characteristics will result. However, this is a majority carrier device, similar to the Schottky diode. If by heat or light minority carriers are generated in the depletion layer, they can partly compensate the charge of the doping atoms in the central layer, decreasing the barrier height and increasing the majority current. Thus the diode also can operate as a photo-diode with internal amplification. The generated minority carriers are captured in the bulk-barrier (as for them it is a potential well) and can leave it only by recombination and at a less extent by diffusion. Therefore, after switching off the light a rather long time is necessary to reestablish the original height of the barrier. This physical picture was verified by transient measurements with a light pulse.

In recent years beside the new devices mentioned in this paper, some others were also reported, making a rather numerous family of new devices. A straightforward systematization of these new devices was done [27], starting from five basic current-amplifying structures. These were the normal pn junction, the tunnel MIS diode, the Schottky junction, the bulk-barrier and the avalanche multiplication effect. The current amplifying structure was defined as a region, where forcing one type of charge carrier current into this region, an opposite type current will result. For example forcing a hole current, an electron current will arrive at the same side of the region. With the help of a separator (collector) this output current can be separeted from the input current, as the two currents are carried by opposite type charge carriers. This collector (separator) effect can be realized by a space-charge region with high electric field. Some amplifying structures also contain a space-charge layer (bulk-barrier diode, reverse-biased MIS diode, avalanche region), thus in these cases it can act as collector and there is no need for a separate collector.

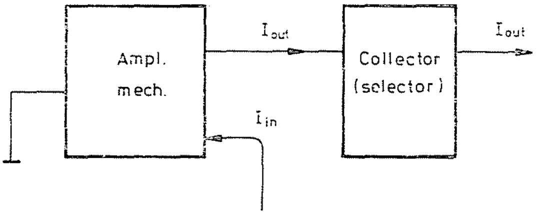

Fig. 5. Schematic structure of an amplifying device

With this scheme many amplifying structures can be created (the most evident is the bipolar transistor), but not all of them have a significant amplification. However, they must also be taken into consideration as everyone can be part of a negative-resistance device. Such a device can be constructed with two amplifying devices, with the condition, that the two amplifiers have opposite type output (or input) currents. With these devices a positive feedback loop can be formed. The two collector regions can be merged into one, thus the general scheme for a current-controlled negative-resistance device can be given as shown in Fig. 6.

The device switches to the low impedance state, if the loop gain exceeds unity. Thus if one amplifying region has a high gain, the device can switch to the low-impedance state, even if the other amplifying region has a low amplification.

With this scheme it was possible to systematize many negative-resistance devices reported in the literature and suggestions were made for some new ones.

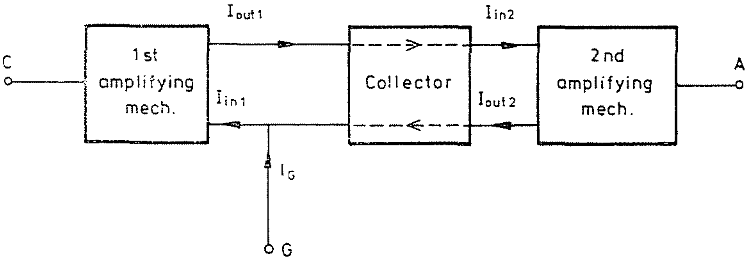

Fig. 6. General scheme of a current-controlled negative-resistance device

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