PREPARATION AND INVESTIGATION OF EXTREME THIN (TUNNELING) SiO_2 LAYERS

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Summary

The role of the thin, tunnel oxide in the new active and negative-resistance devices is discussed. The preparation of such a thin oxide is described. A new method is outlined, by which after metallization it can be checked whether the grown oxide is apt for applying in these devices.

In the last years some new devices were presented applying the tunneling of holes and electrons across extreme thin (2—4 nm) oxide layers between metal and semiconductor. The basis of these devices is the amplifying mechanism in a metal-(tunneling) insulator-semiconductor structure (Fig. 1.a) discovered by Shewchun [1, 2]. With two of these MIS structures a device can be formed, if the distance between them is small enough, called the surface oxide transistor (SOT) [3, 4] which has a bipolar transistor-like I—V characteristics (Fig. 1.b). The same structure, with a different biasing circuit, can also exhibit an S-type negative resistance I—V characteristics [5, 6]. If the amplifying MIS structure is combined with a p^+n junction ($m-i-n-p^+$), another device, the metal-insulator-semiconductor switch (MISS) results (Fig. 1.c) with a similarly S-type negative resistance I—V characteristics [7, 8, 9, 10]. In some cases a negative resistance characteristics was found even without a $p-n$ junction as a result of hot-electron effects.

The functioning of all these devices depends upon the forming of a special, non-equilibrium inversion layer at the metal-semiconductor interface. Without additional minority-carrier generation or injection the insulator-semiconductor interface is in a deep-depletion state, there is no inversion layer, because the oxide is thin enough to allow the passing of minority carriers generated thermally in the depletion layer to the metal. At thicker oxides (over about 4 nm) even these thermally generated minority carriers can form an inversion layer and as a result the amplifying mechanism disappears.

If by illumination or by injection the supply of minority carriers is highly enhanced, an inversion layer can be found at the oxide-semiconductor interface. This can, however, be accomplished only if the oxide is not very thin

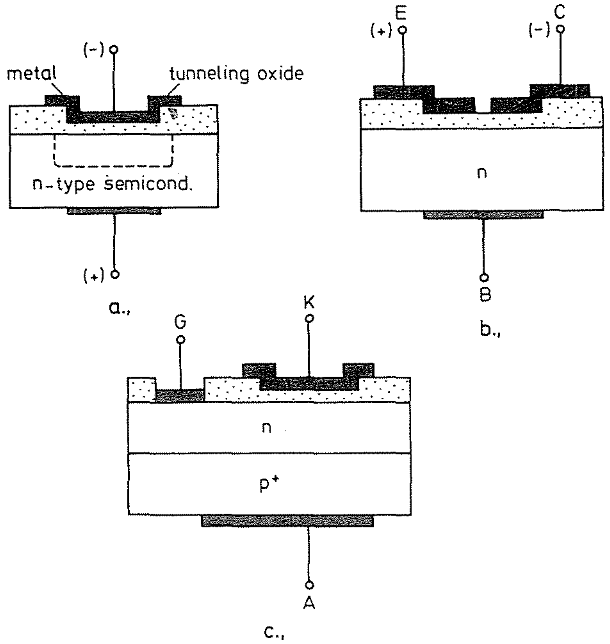

Fig. 1. Tunnel-oxide active devices. a., amplifying MIS structure; b., surface oxide transistor (SOT) and MISIM; c., MISS and MIST

(thicker than 1,5—2 nm). If the oxide is very thin, the resulting very high tunneling current practically forms a short circuit between the metal and the semiconductor, and there is not any amplifying mechanism.

If an inversion layer can be formed, the charge in this layer is influenced by the injected (generated) minority charge-carrier current. By increasing the inversion charge the field-strength in the insulator (oxide) is increased, which increases the (tunnel) injection of majority carriers from the metal into the semiconductor, and thus the total current as well.

The extreme thin oxide layer can be produced in different ways, but the most suitable way seems to be the thermal growth of silicon dioxide. However, in contrast to the usual, thick-oxide growing methods, a very low growing rate is necessary and so the oxidation temperature is significantly lower than in the case of thicker oxides. Typical oxidation temperatures are between 700 °C and 800 °C, in pure, dry oxygen at atmospheric pressure. Typical oxidation times are 5...20 min. At higher temperature the necessary oxidation time is shorter.

Oxidation experiments were carried out at 700 °C and 800 °C oxidation temperatures, at atmospheric pressure, in dry oxygen. Before oxidation the wafers were cleaned and etched in HF solution. After oxidation the samples were annealed in nitrogen at the same temperature for 30 minutes.

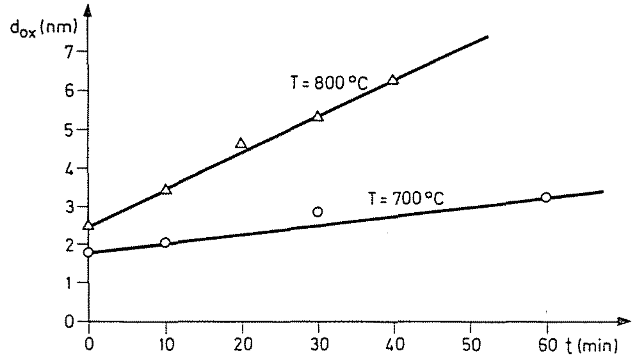

Fig. 2. Oxide thickness versus oxidation time at 700 °C and 800 °C temperatures, in pure dry oxygen, at atmospheric pressure

The oxide thickness was measured by an ellypsometer. The results are shown in Fig. 2 for 700 °C and for 800 °C oxidation temperatures, where the resulting oxide thicknesses versus the oxidation times can be seen. The growth rate is significantly higher at 800 °C than at 700 °C. For the oxide thickness which is necessary for the afore-mentioned active devices, the oxidation times at 700 °C are about 15. . .40 min. However, at 800 °C these times are much shorter, they are between 3 and 10 minutes. The higher temperature is, however, more advantageous from the point of view of fixed surface charge and surface states.

As is well known, the oxide thickness is a linear function of the oxidation time in the case of thin oxides. However, extrapolating the oxide thickness back to zero oxidation time one does not get zero oxide thickness, but a final value. This is the initial phase of the oxidation, when very quickly a thin, about 1—1,5 nm thick oxide layer forms.

In our case this initial oxide seemed to be a little thicker as known in literature, but it can be partly the result of the higher measuring error at such thin layers.

There is world-wide a significant research effort undertaken to clarify the stoichiometric composition of the oxide-silicon interface. It seems that there is a transition layer between oxide and silicon with a thickness of about 0,8. . . 1 nm, where a continuous transition from oxide to silicon takes place. The initial anomalous oxide growth is very probably in connection with this transition layer. With the aid of the C—V curve of the MIS structure it can be checked, whether the oxide thickness is apt to form an active inversion layer. The C—V curve of a tunneling MIS structure with n-type substrate is shown in Fig. 3. Without additional minority charge-carrier generation the surface is in deep depletion in the case of negative bias voltage, therefore the capacitance of the device is decreasing with an increasing (reverse) bias voltage. (curve 1) If the device is illuminated, an inversion layer forms at the oxide semiconductor interface, and the capacitance approximates a constant value (curve 2). Increasing the reverse bias, however, increases the tunnel current of the minority carriers across the oxide as a result of the bigger field-strength in the oxide, and if this tunnel current becomes larger than the fotogeneration current, the inversion layer as well as the width of the depletion layer starts to increase which leads to the decrease of the capacitance of the device. Thus at a sufficiently high voltage the inversion layer disappears completely and the C—V curve approximates the one without illumination. If the illumination is stronger or the oxide is thicker, the capacitance starts to decrease at a higher voltage (curve 3).

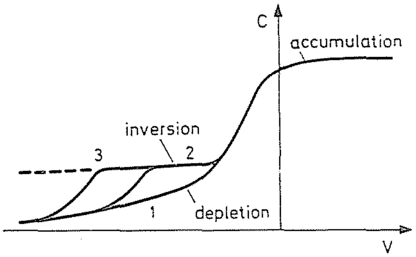

Fig. 3. Schematical high-frequency C—V curve of the MIS tunnel structure 1., in darkness, 2., under illumination 3., under strong illumination

At thicker oxides the capacitance saturates even without illumination as an inversion layer is formed by the thermal generation current in the surface depletion layer. If the oxide is not very thick yet, there is a little tunnel current across it, which increases quickly with the bias voltage. After a while it will be larger than the generation current and the capacitance will thus decrease. As the oxide thickness will be even thicker, the leakage across the oxide will be negligible and the capacitance will be constant as it is well known for high-frequency capacitances of thick-oxide. Thus by measuring the high-frequency C—V curve of the tunneling MIS structure one can easily check whether the grown oxide is suitable for the preparation of a tunnel-oxide active device or not. The most favourable case is when, without illumination, the surface is in deep depletion but when applying illumination, the capacitance saturates according to the formation of an inversion layer at lower reverse voltages, then starts to decrease again at higher reverse bias voltages as a result of the reduction, and finally of the disappearance of the inversion layer. The measuring of the oxide thickness before metallization gives no accurate information. During metallization the metal and the oxide forms a transition region, its thickness can be in the same order of magnitude as that of the thin oxide itself.

Considering that there is another transition layer between the oxide and the silicon, one can guess that the final composition of the insulator is rather different from the ideal silicon-dioxide. The theoretical models have taken into account only an ideal oxide layer, up to now.

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