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CURRENT CONDUCTING MECHANISM AND NEGATIVE RESISTANCE N-AND S-TYPES IN THE Al-Al_2O_3-Ag TUNNEL STRUCTURE

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We have analyzed the scientific publications of research the electrophysical properties of thin films metal-oxide-metal (Al-Al_2O_3-M) (MOM) structures. Some of them reported either the N-type or the S-type negative resistance on the I-V characteristics of these structures. The differing results are due to oxide layer was fabricated in a variety of ways and selection of upper electrode. On the characteristics of the Al-Al_2O_3-M structures with the oxide layer, produced by air exposit and silver as an upper electrode, we observed the regions of negative resistance of the N-and S-type for the first time.

The procedure of fabricating an Al-Al_2O_3-Ag structure was as follows: an oxide layer (Al_2O_3) 30-80 Å thick was grown exposing to air the Al film thermally deposited onto glass, ceramic or any other neutral substrate, heated to 150-170^{0}C, in vacuum ~$5*10^{-6}$mm. mercury column. Aluminum oxide obtained in this way is free of impurities and best of all corresponds to stoichiometric composition [1].

The upper electrode was then vacuum deposited onto the obtained oxide. The I-V characteristics were recorded statistically by standard technique and on bi-co-ordinates characteriograph. Fig. 1 shows the statistic and oscillogram of the I-V characteristics for an Al-Al_2O_3-Ag structure with effective area ~1.07 sq.mm and oxide thickness ~60 Å at room temperature.

Fig. 1. Statistic I-V characteristic and oscillogram for the Al-Al_2O_3-Ag structure at room temperature.

We started to record the I-V characteristics with the application of negative bias to aluminum electrode. As one can see, at low voltages the samples are in low-ohmic (open) state, which is conserved to a voltage of U≤1.0V. At U=0.8-1.0V the current reaches its maximum and decreases with the increasing voltage. At ~2.0V the current passes through a minimum. Thus, the N-type negative resistance is observed. Continued increase in voltage leads to monotonic increase of the current and at ~3.7V it increases sharply, i.e. the S-type negative resistance is observed. New low-ohmic state has a larger steepness than that of the N-shaped portion of characteristic. The I-V characteristic is symmetric at both polarities of the applied voltages. Consequently, the characteristic of the Al-Al_2O_3-Ag structure is unusual, namely: at room temperature the structure has a I-V characteristic with the N-and following it S-portion.

The representative parameters of switching-cutoff voltage and current (U_{cutoff}, I_{cutoff}) voltage and current in the minimum of N-shaped portion of the I-V characteristic-(U_{min}, I_{min}), voltage and current of switching-on (U_{on}, I_{on}) and switching-off (U_{off}, I_{off}) of the sample assume the following values: U_{cutoff} ≤1.0V, I_{cutoff} ≤30mA; U_{min} ≤2.3V, I_{min} ≤2mA; U_{on} ≤3.8V, I_{on} ≤10mA. Residual voltage (U_{res}) on the structure in the switched state does not exceed 1.5V, while the residual current (I_{res}) ~100mA, and is also limited by the external circuit resistance. In decreasing the voltage to zero the structure remailns in low-ohmic state, which is retained even on changing the polarity of the applied voltage up to the value of current $I_{off} \geq I_{residual}$ at which the structure is switched over into the high-ohmic state. In this state $I_{res} \geq I_{on}$ and $U_{res} \geq U_{on}$. As the voltage decreases the current essentially follows the same high –ohmic characteristic, preceded switching.

At repeated measurements the course of the observed phenomenal and the values of the above parameters are retained. Cut out the applied voltage and changing the polarity one the structure keep in memory its final state. The obtained the I-V characteristics proved to be sensitive to the environmental temperature. Fig. 2 shows the I-V characteristics of the structure in the temperature interval 77-363 K-Al.

Fig. 2. Temperature dependence of the I-V characteristic (T, K); 1-363; 2-348; 3-323; 4-300; 5-273; 6-250; 7-213; 8-183; 9-173. Above: Temperature dependence of the “on” voltage.

One can see that the S-and N type switching is observable both-at high and low temperatures. N-type state evident is seen at room temperature. Rise above of room temperature the switching from low-ohmic to high-ohmic state (N-type) appeares under change of applied voltage polarity.

The value for the switching-on voltage (U_{on})-the voltage at which the structure transfers from high-ohmic state to low-ohmic one-turned out to be a temperature dependent value. Above of fig. 2 represents the plot of lgU_{on} as a function of $10^3/T$, from where it follows that in the interval 273-363 K U_{on} is strongly dependent on temperature, as compared with the interval 173-273 K.

It's clear from fig. 2 that the steepness of the I-V characteristics on it low-ohmic portion decreases with increasing temperature. This points to metal character of the resistance of the structure in low-ohmic state.

Prior to temperature measurements, the samples were subjected to heat treatment. For this purpose they were first placed into liquid nitrogen, then heated to 100^0-110^0 C and again cooled to room temperature. Our investigations revealed that the obtained results are adequately reproduced after such a heat treatment.

The analysis of the I-V characteristics revealed that at low-ohmic branches the Ohm's Law is executing. Fig. 3 depicts the high-ohmic branch of the I-V characteristic (the second ascending portion of the N-shaped I-V characteristics) at various temperatures (173-36 K).

Fig. 3. The high-ohmic branch of the I-V characteristic for the Al-Al_2O_3-Ag structure in Fowler-Nordheim coordinates at various temperatures (T, K): 1-173; 2-183; 3-213; 4-250; 5-273; 6-300; 7-323; 8-348; 9-363.

One can see that in the whole temperature interval the I-V characteristics fall well on a straight line in coordinates described by Fowler-Nordheim dependence:

$$\mathrm{I} \sim \exp\left[-\frac{4\sqrt{2m*(q\varphi)^3}\,h}{3qtvE}\right] \qquad (1)$$

This indicates to the presence of tunnel conduction mechanism, i. e. tunnel-effect stimulated transfer of charge carriers through the oxide film.

The slope of the characteristics remains practically unaffected with the temperature change. From the temperature dependence of the current through the structure (fig. 4) at fixed values of the applied voltage it will be obvious that the current increases proportionally to T^2 in accordance with the expression.:

Fig. 4. Temperature dependence of the current through the Al-Al_2O_3-Ag structure in its high-ohmic state at fixed values of voltage.

$j(T)=j(0)+ \alpha T^2$ (where α is the coefficient of the current variation with temperature), which also speaks in favor of tunnel effect.

Using the tunnel characteristics one can find the effective height of the potential barrier (Φ) on the oxide interfaces-one the significant parameters determining the current through the system involved. The Gundlach function [2].

$$Q=(1/\Delta u) \ln[I(u+\Delta u)/I(u) \quad (2)$$

constructed to the currents I_1 and I_2, flowing in different directions has sharp peaks at voltages near Φ_1 and Φ_2.

Fig. 5 represents the voltage, corresponding to Q_1 and Q_2. To judge by the position of peaks, the heights of the potential barriers on Al-Al_2O_3 and Al_2O_3-Ag interfaces are equal to ~2.2 and 2.26 eV, respectively.

The analysis of the I-V characteristic in the region 0.7-2.0 V showed that the dependence of the current through the structure on the applied voltage in the region 0.8-1.2V is well described by the $\exp(u^{1/2})$ law, peculiar to the Schottky emission. Indeed, as one can see from fig. 6, the I-V characteristic is well approximated by a straight line in the $\lg I \sim u^{1/2}$ coordinates.

Fig. 5. Variation of Q_1 and Q_2-logarithmic derivations of I_1 and I_2 found by the I-V characteristic of the Al-Al_2O_3-Ag structure-with voltage at room temperature.

Fig. 6. The high-ohmic branch of the Al-Al_2O_3-Ag structure in the Schottky coordinates between 0.8 and 1.3 V.

In the region 1.2-2.0V the Richardson-Schottky conductivity transfers to tunnel emission. The slope of the lgI~f($u^{+1/2}$) determined from fig. 6 gives the value equal to~2.51$V^{-1/2}$ (β_s). According to the relation [3]:

$$\beta_s = \frac{0.43q^{3/2}}{kT\sqrt{4\pi\varepsilon_r\varepsilon_0 d}} \qquad (3)$$

In the expression:
T-absolute temperature;
ε_r-relative dielectric constant of the insulator;
ε_0-electric constant of vacuum;
k-the Boltzmann's constant;
d-thickness of dielectric layer;
qφ-height of potential barrier on contact-dielectric interface;
E-electric field;
q-electron charge.

Calculation by the formula (3) at ε_r=12 d=60 Å showed that β_s=2.40$V^{-1/2}$ which is very close to the experimental value β_s (2.51$V^{-1/2}$). An agreement between the theoretical and experimental values of the coefficient β_s provides support for the presence of the Schottky (above barrier) emission into aluminum oxide film in the region 0.8-1.2V. This allows to calculate the height of the potential barrier (Φ=qφ) on the oxide Al_2O_3 interfaces. From the expression (3) it follows that

$$q\varphi = -\frac{kT}{0.43}\lg\frac{I}{SAT^2} \qquad (4)$$

where:
A-Richardson's constant-120A/см^2*grad^2;
S-the area of the structure under investigation (1.07 sq. mm);

I-the cutoff current which can be found by extrapolating the linear portion of the I-V characteristic in the lgI~$U^{1/2}$ coordinates (fig. 6) to the zero voltage. The substitution of numerical values into the expression (4) gives φ=0.73 eV for the height of potential barrier on lower electrode-oxide (Al-Al_2O_3) interface. The height of the potential barrier on the oxide-upper electrode interface, (Al_2O_3-Ag) estimated in the similar way turned out to be ~0.79 eV. As on the theory, the difference in the estimated values for φ_1 and φ_2 (0.06 eV) coincides with the difference in the work function (~0.05 eV) of aluminum and silver. As may be seen from fig. 6 at ~1.3 V one observes a deviation from the Schottky law. By the magnitude of this voltage the authors [4] have proposed a simple and precise method of determining the effective electron mass (m^x) in insulators and semiconductors by the formula:

$$m^x = \left(\frac{h\sqrt[4]{q\varepsilon}}{1.76\pi^2 kT}\right)^2 E^{3/2} \qquad (4)$$

where:
h-the Plank's constant;
q-electron charge;
ε-dielectric constant of the mateial;
E-electric field intensity, at which one observes a deviation from the Schottky law in the region between thermoelectric and field thermionic emission.

Calculation by the formula (4) at ε_r=12 gives $\frac{m^x}{m_o} = 1.62$ which is close to the value for the effective electron mass-1.78m_o for Al_2O_3 found in [4].

A knowledge of the effective mass in its turn, also allows to estimate the height of potential barrier on the oxide interfaces.

In accordance with the Fowler-Nordheim formula(1) the slope of the lgI~U^{-1} dependence is given by the formula:

$$tg\alpha = \frac{0.43 * 4\sqrt{m^x}\,(q\varphi)^{3/2}}{3qh} \qquad (6)$$

with m^x $1.62m_0$gives the value of φ=0.71 eV on Al-Al_2O_3 interface which is very much like a height of the barrier on the same interface, we have determined from the low for Schottky emission (~0.73 eV)

Discussion of the results

The presence of the N-and S shaped portions on the current-voltage characteristics of the Al-Al_2O_3-Ag structure results from the fact that at low voltages its reactive impedance has a capacitate character which further increase of voltage converts to the inductive one, i. e. a negative current feed-back gives way to a positive feed-back. The internal negative current feed-back seems to be due to the fact that increase of the applied field leads to an increase in capture cross section of the levels in the Al_2O_3 forbidden band in the process of depositing silver electrode. In the Al-Al_2O_3-M structures, with other materials of the upper electrode (Al, Zn, Cu, Su) or in the presence of intermediate semiconducting layer between the oxide and upper electrode (MOSM-structure) no N-shaped portion of the I-V characteristics is available.

The internal positive current feed-back conditioning the S-type negative resistance region is produced by the fact that at a voltage almost equal to a half width of the Al_2O_3 forbidden band (~3.7 V), the Fermi level of positively charged electrode (anode) is so decreased that it nearly coincides with dielectric valence band and electrons tunneled from dielectric valence band into electrode prevail in the conductivity. Because of this the current through the structure sharply increases and the structure transfers to high-conducting state. The temperature dependence of "on" voltage (fig. 2) points to thermal activation trap levels superimposing starting from ~273 K.

The analysis of field and temperature dependencies of conductivity for the structures studied illustrated current through them to be due to tunnel effect and Schottky effect.

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Al-Al_2 O_3 ƏSASLI TUNNEL STRUKTURLARDA KEÇİRİCİLİK MEXANİZMİ VƏ N-, S- TİPLİ MƏNFİ MÜQAVİMƏT

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İlk dəfə Al-Al_2 O_3 (60Å) - Ag strukturunun volt – amper asılılığında N və onun ardınca S – tip mənfi müqavimət aşkar edilib, yəni kiçik gərginliklə reaktiv impedansı tutum səciyyəli olan struktur, gərginlik artıqda induktiv xarakter kəsb edir. (173 - 363)K intervalında cərəyan – keçirmə və aşirma mexanizmi öyrənilib. Cərəyanın temperatur və elektrik sahəsindən asılılığında təyin edilibki həmin strukturda cərəyankeçirmə tunnel və Şottki mexanizmi ilə tənzimlənir. N- tipli mənfi mügavimət Al_2O_3 təbəqəsinin qadağan zolağındaki tələlərə elektronların cəzb olunması, S – tip mənfi müqavimət isə tunnel effekti – yəni oksid layının valent zolagından elektronların güclü elektrik sahəsinin təsiri ilə elektroda keçməsiylə izah

olunur. Oksid – metal sərhəddində potensial səddin hündürlüyü və Al_2O_3 – də elektronların effektiv kütləsi təyin olunub.

МЕХАНИЗМ ЭЛЕКТРОПРОВОДНОСТИ И ОТРИЦАТЕЛЬНОЕ СОПРОТИВЛЕНИЕ N – И S –ТИПОВ В ТУННЕЛЬНОЙ СТРУКТУРЕ Al-Al_2O_3-Ag

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Впервые на ВАХ тонкопленочной структуры Al-Al2O3-Ag, с окисной пленкой 60 Ǻ , полученной зкспонированием на воздухе алюминиевой пленки, обнаружено отрицательное сопротивление (ОС) N-и следующее за ним S-типа. В широком интервале температур изучены явления переноса и переключения в этих структурах. Из полевой и температурной зависимостей проводимости структуры установлено, что токопрохождение через нее обусловлено туннельным эффектом и эффектом Шоттки. ОС N-типа инициировано захватом электронов на ловушки в запрещенной зоне Al_2O_3, а S-типа туннелированием электронов из валентной зоны окисла в электрод под действием сильного электрического поля. Определены высоты потенциальных барьеров на границах окисла с металлом и эффективная масса электронов в Al_2O_3.

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