Ultrathin film deposition for nanoelectronic device manufacturing

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Abstract Study results of thin film with thickness less than 50 nm deposition by means of electron beam evaporation on special vacuum coaters were represented. Calculation results of energy and mass carry magnitude for ITO, Ag and Al thin films deposition with preset of structure and composition homogeneity and roughness were shown.

1. Introduction
Thin film deposition opportunity with thickness less than 50 nm and preset of quality characteristics depends on energy and mass carry magnitude [1]. Thin film generation particles energy depends on thin film deposition method, and thin film generation particles mass flow depends on source conditions and distance from the source and substrate. So, ultrathin and ultrasmooth and uniform thin films with crystal structure and homogeneous composition can be deposited by means of a little deposition rate and particle energy, substrate high temperature and high vacuum as well.

Electron beam evaporation method corresponds to all of the enumerated requests [2]. The science and education center of Bauman Moscow State Technical University has the special vacuum electron beam equipment for nanostructured thin films manufacturing of nanoplasmonic and quantum calculation devices for modern nanoelectronics.

2. The special vacuum technological equipment
The vacuum coater «EvoVac Angstrom Engineering» consists of pumpdown system (spiral forevacuum and cryogen high vacuum pumps) and technological sources (electron tween beams evaporator with seven melting pots and ion source with hollow cathode) and vacuum chamber with height adjusting and turning with forty revolutions per minute 200-mm substrate holder. The substrate holder can be heated up to 773 K and can be cooled up to liquid nitrogen temperature as well. Also there are two sensors of thin film deposition rate and film thickness optic monitoring into the vacuum chamber. Unevenness of thin film thickness on 200-mm substrate unexceeds of ± 2 %.

The vacuum electron beam evaporating coater Plassys MEB550 SL3 is intended for metallic and oxide thin films deposition. The preset of thin oxide film stoichiometry is provided by means of oxygen flow supply into vacuum chamber control. Substrates can be heated up to 873 K and substrate surface can be cleaned before thin film deposition by means of argon plasma discharge. The coater consists of three chambers with the next pressure in it: $3 \times 10^{-6}$ Pa in loading chamber, $10^{-7}$ Pa in metallic thin film deposition chamber, $10^{-6}$ Pa in oxidation chamber. All of three chambers are pumped by means of Edwards spiral forevacuum and turbomolecular high vacuum pumps.

There are 100-mm substrate holder with three variance and automatic control system for thin film deposition on preset algorithm at the coater.
3. Electron beam ultrathin films deposition examples

10 – 20-nm Indium Tin Oxide (ITO) thin films are used at optic modulators as a transparent conducting oxide. Method of ITO thin film deposition was electron beam evaporation. In$_2$O$_3$ and SnO granules were evaporated by electron beam with a pressure of $10^{-5}$ Pa and were deposited on silicon substrate. There was ion assistance of thin film condensation and 0.2 nm/sec thin film deposition rate was controlled by means of a quartz sensor.

The main element of superconductive cubits for quantum calculation is Josephson’s junction (Fig. 1) – three layers structure as “superconductor – dielectric – superconductor”.

![Josephson's junction](image)

100-nm thin aluminum film as a superconductor was deposited by electron beam evaporation method on Plassys MEB550 SL3 coater. Unified vacuum cycle of thin film deposition with 2 – 10 Å/sec rate was used for providing precise manufacture of 1.5-nm dielectric layer as a tunnel barrier.

Manufactured thin films had uniform of 100% and roughness less than 2 nm. Thin film deposition rate influence to thin film roughness is shown at Fig. 2. Received experimental results point out that thin film roughness minimum can be deposited on 0.5 nm/sec rate.

40-nm silver films with mono crystal structure and uniform of 100% and roughness less than 1 nm are the best material for nanoplasmonics. Such films was manufactured by means of EvoVac Angstrom Engineering coater on $10^{-5}$ Pa pressure and substrates temperature of 400 – 800 K and thin film deposition rate of 0.1 – 0.4 nm/sec as well.

It is possible to provide thin film deposition rates of 0.1 – 0.4 nm/sec by electron beam evaporation only if material temperature in melting pot corresponds with preset saturated vapor pressure of thin film material.
Figure 2. The influence of thin film rate $V_d$ to thin film surface roughness $R_q$

The experimental research of an influence of silver crystal dimension from substrate temperature (Fig.3) and thin silver film rate (Fig.4) were carried out. The theoretical dependence of aluminum and silver thin film deposition rate $V_d$ from heating temperature of thin film materials up to evaporation temperature $T_e$ with corresponding saturated vapor pressure are represented on Fig. 5.

Figure 3. The influence of silver crystal dimension $L$ from substrate temperature $T$
Figure 4. The influence of silver crystal dimension $L$ from thin film deposition rate $V_d$

Figure 5. The influence of thin aluminum and silver films rate $V_d$ from evaporation temperature $T_e$

Thin aluminum and silver films deposition rate $V_d$ calculation were shown that to provide the thin films deposition rate of $0.1 - 0.4$ nm/sec the electron beam evaporator melting pot temperature $T_e$ must provide $10^{-2} - 10^{-3}$ Pa saturated vapor pressure. So, thin silver film deposition rate can be approximately equaled
where \( M \) is molecule mass, \( \text{kg/kmol} \); \( \rho \) is material density, \( \text{kg/m}^3 \).

For thin aluminum film:

\[
V_d = 5.83 \cdot 10^{-3} \cdot 10^{-3} \cdot \frac{108}{1195} \cdot \frac{10^9}{1050} = 0.16 \text{ nm/sec},
\]

Energy and mass carry magnitude of thin silver film is equal:

\[
E_V = 2.88 \cdot 10^{-26} \frac{J \cdot kg}{m^2 \text{sec}}
\]

or \( 1.8 \cdot 10^{-7} \text{ eV kg/(m}^2\text{sec)} \),

where \( k \) is Boltzman constant.

Energy and mass carry magnitude of thin aluminum film is equal:

\[
E_V = 1.38 \cdot 10^{-23} \frac{J \cdot kg}{m^2 \text{sec}}
\]

or \( 9 \cdot 10^{-8} \text{ eV kg/(m}^2\text{sec)} \).

Conclusion
Thin ITO films were deposited by means of electron beam evaporation method on special vacuum coater for transparent electrode with 10 – 20 nm thickness manufacturing. Al-AlO\(_x\)-Al josephson’s junction and thin silver films for nanoplasmonics were manufactured by means of electron beam evaporation method as well. All of 100-nm thin aluminum film and 1,5-nm thin dielectric film and 40-nm thin silver film were deposited with 0,1 – 10 nm/sec deposition rate. All of this thin film had the structure, uniform composition, roughness and thickness unevenness which were corresponded preset characteristics.

So, the results are asserted that to obtain the energy and mass carry magnitude about \( 1 \cdot 10^{-7} \text{ eV kg/(m}^2\text{sec)} \) for mono crystal thin films manufacture [3] one can by means of electron beam evaporation method. Meanwhile it is necessary to have precise monitoring of thin film deposition rate or to have an opportunity of material at melting pot measurement to provide preset saturated vapor pressure.

References
[1] Y V Panfilov Nanostructured thin film deposition methods selection by “energy mass transfer” criterion / Nanoengineering, 2016, №12, P. 3 – 10.
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[3] Monocrystalline films. Under edition of Pinsker, Mir, 1966, 400 pp.

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V_d = 5.83 \cdot 10^{-3} \rho \frac{M}{T_e} \frac{10^9}{\sqrt{1355 \cdot 2700}} = 0.3 \text{ nm/sec}.
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