Моделирование отказов элементов металлизации микро- и наноэлектронных устройств под действием электромиграции

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Key problems in failure modeling are to model (i) vacancy/ion transfer and accumulation, and (ii) defect nucleation and growth induced by these processes

This work presents a full 3D theory and the results of a computer simulation of electromigration-induced nano- and microprocesses that terminate in failure of thin-film conducting elements. These processes determine operational reliability and lifetime of IC metallization

Empirical relation of Black (1969)

$$TTF = Aj^{-n}\exp\left(\frac{E_a}{kT}\right)$$

j is the current density,

E_a is the activation energy of grain boundary diffusion,

A is the parameter depending on the material, process of line formation, conductor structure and geometry,

$n \geq 1$ is the constant whose value essentially depends on the range of the *j* values used (*n* increases with *j* growth)

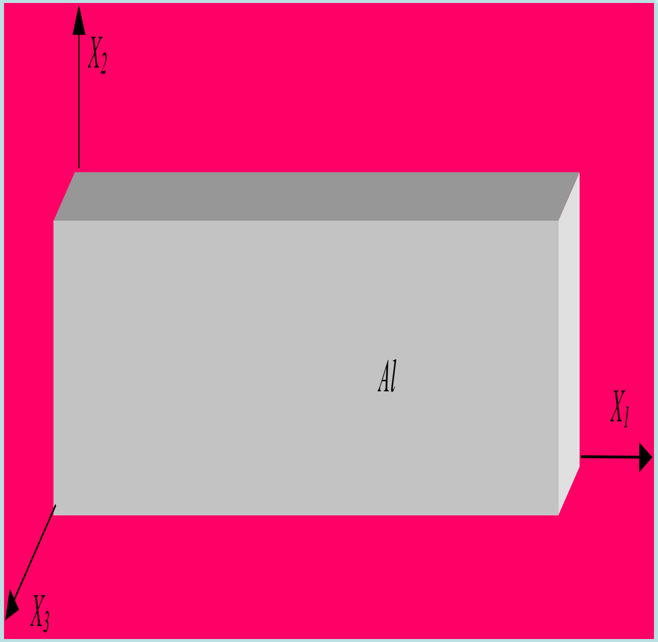
T. Makhviladze, M. Sarychev, and K. Valiev (1989) - microscopic theory

T. Makhviladze, M. Sarychev, and K. Valiev (1990 - 1991) - more general model

THEORY OF ELECTROMIGRATION DEGRADATION AND FAILURES (MAIN EQUATIONS)

VACANCY TRANSPORT AND STRESS GENERATION

$$\frac{\partial C}{\partial t} + \nabla_i q_i = F_v(x_1, x_2, x_3, t), \quad q_i = D\left(-\nabla_i C + \frac{CZ^*}{kT\sigma_0} j_i + \frac{C}{k\ T} \varepsilon_v \frac{\partial \sigma}{\partial x_i} \right)$$



$C(x_1, x_2, x_3, t)$ is the vacancy concentration,

q_i is the i-th component of the diffusion flow,

$F_v(x_1, x_2, x3, t)$ is the source function describing vacancy generation and annihilation,

D is the vacancy diffusion coefficient,

Z^* is the effective vacancy charge,

$j(x_1, x_2, x_3)$ is the current density vector,

$\sigma(x_1, x_2, x_3, t) = (\sigma_{11} + \sigma_{22} + \sigma_{33})/3$ is the spherical component σ of the mechanical stress tensor σij which describes triaxial compression ,

ε_v is the elastic volume strain induced by the relaxation of the vacancy volume ($\varepsilon_v = = -f\,\Omega < 0$ with the relaxation coefficient f, Ω is the specific atomic volume of the conducting material),

σ_0 is the conductivity

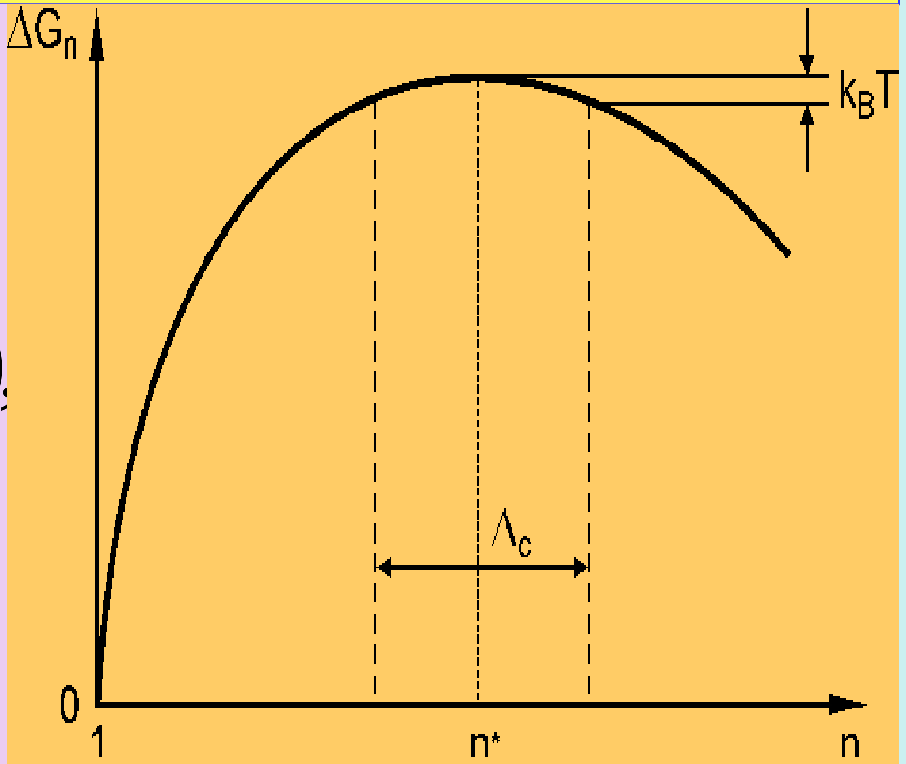
VACANCY CLUSTER NUCLEATION KINETICS AND DETERMINATION OF THE MICROVOID NUCLEATION TIME

The equilibrium concentration of vacancy clusters of size *n* is

$$c_0(n) = c_0(1)\exp(-\Delta G_n/kT),$$

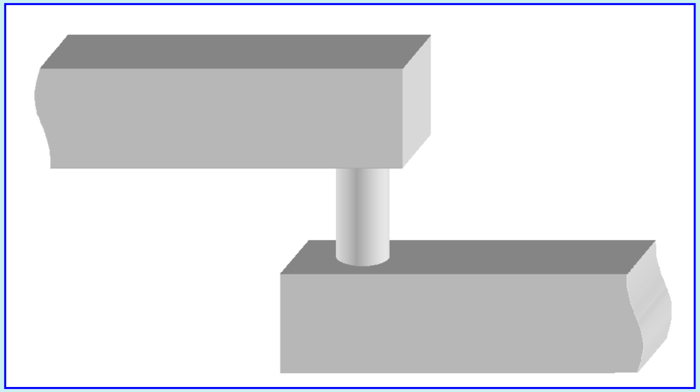
where $c_0(1)$ is the equilibrium concentration of vacancies,

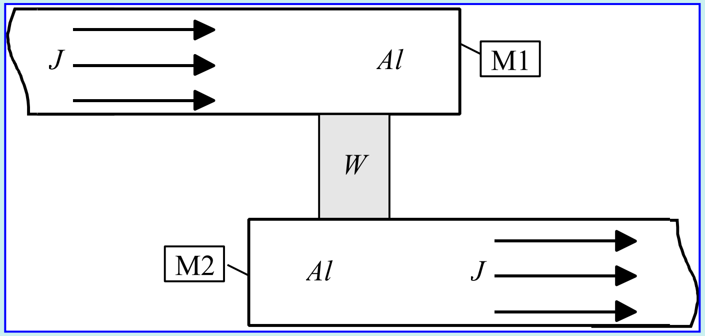
ΔG_n is the change in Gibbs free energy resulting from the formation of a vacancy cluster of size *n*.



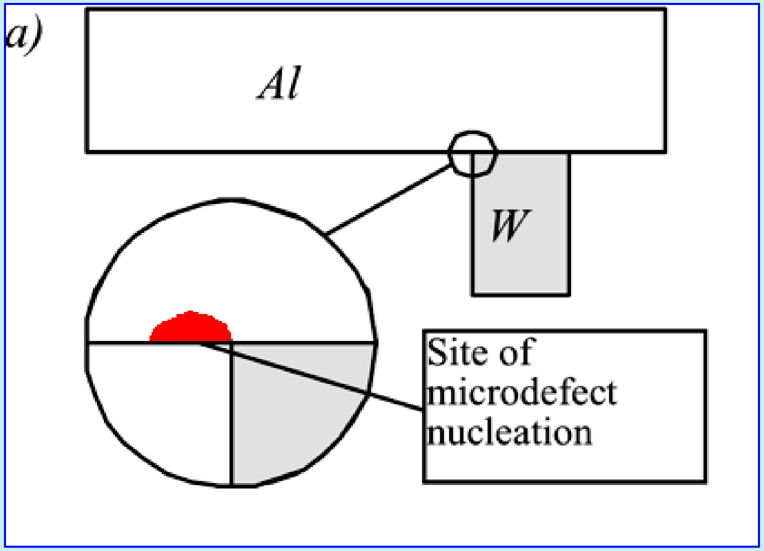
Qualitative relationship between Gibbs free energy variation and cluster size. Δc is the width of the domain on the size axis where the free energy variation differs by no more than $k_B T$ from its maximum value

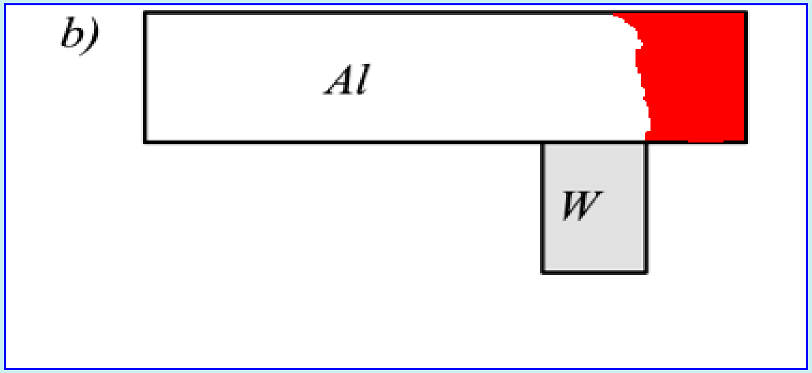
MULTILEVEL-METALLIZATION DEGRADATION AND FAILURE





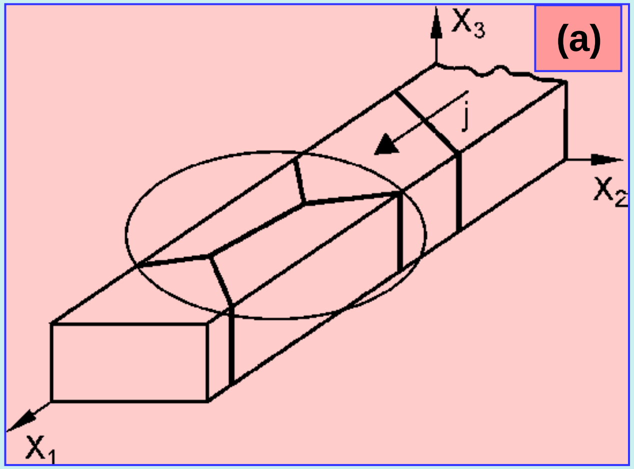
Two-level metallization with the AL conducting lines interconnected by a tungstem via

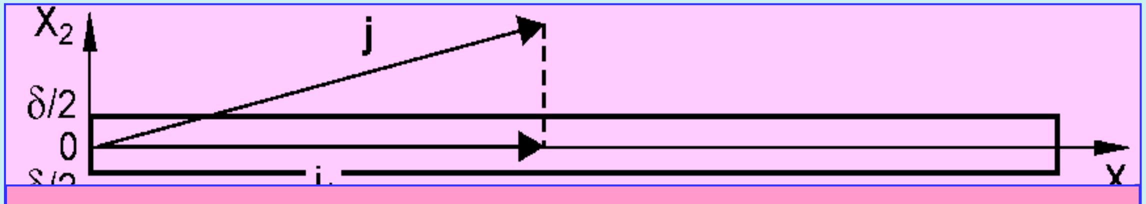




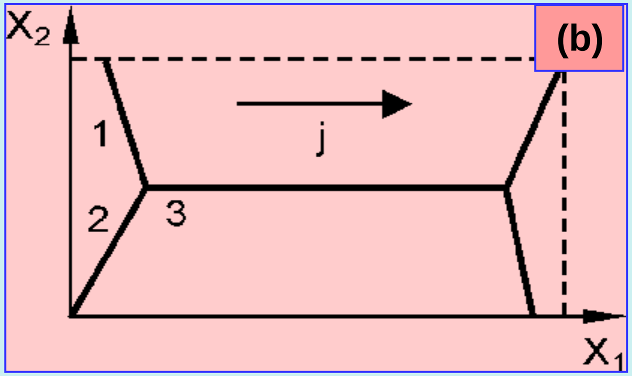
Two possible mechanisms of metallization failure: (a) voiding and (b) surface erosion

POLYCRYSTALLINE INTERCONNECT DEGRADATION AND BULK FAILURE





Frame of reference relative to a rectilinear grain boundary part. δ is the grain boundary width, j_1 is the projection of the current density vector on the X_1 axis



Conducting line (substrate and coating not depicted) (a); top view of the line segment under study (the digits denote rectilinear parts of the grain boundary converging in the triple point) (b)

The used values of parameters

Bulk modulus B = 60 GPa,
$\rho_0 = 3 \cdot 10^{-8}$ Ohm · m
Effective vacancy charge $Z^* = 12|e|$ (e is the electron charge),
Activation energy of grain-boundary diffusion $E_a^{GB} = 0.6$ eV,
Activation energy of bulk diffusion $E_a^{B} = 1.2$ eV,
f =0.2,
Interatomic distance $a = 2.5 \cdot 10^{-10}$ m,
Volume of a unit cell $\Omega = 1.66 \cdot 10^{-29}$ m3,
Grain boundary width δ = 0.5 nm
Segment length 2 mkm

Cu metallization degradation: Problems and Features

- **Failure kinetics: vacancy electromigration, generation of mechanical stress and deformation, nucleation and growth of vacancy clusters (j > 10^5 -10^6 A/cm2)**

- **Growth of thermodynamically stable microvoids from nanometer size up to transverse size of the line (up to grain size, for bamboo structures)**

- **Competition of different electromigration failure modes in the contact areas of conducting lines:**
  1) microvoid growth in the vicinity of contact plug connections between the adjacent metallization levels
  2) open edge erosion of the conducting line as a result of vacancy migration to the open end of a line
  The other failure modes:
  3) microvoid growth at the line - isolating dielectric interface (deep into the line bulk)
  4) microvoid growth in the bulk of polycrystalline line due to grain boundaries electromigration and stable cluster nucleation in the triple points (less important for Cu compared with Al)

- **Adhesion strength of interfaces subjected to the action of electrical, mechanical and thermal load and its dependence on defectiveness of joining materials (no exfoliation, hogging etc.)**
  Interfaces and contacts: conducting line (CL) - barrier film layer, CL – protective dielectric, CL – layer introduced between CL and plug to improve adhesive power (Ta, TaN, TiN); metal electrodes - high-K dielectric – high mobility semiconductors

- **Optimization of interconnect adhesion strength with respect to defect concentrations and distributions, boundary texture, and operating parameters**

- **Resistivity increase and heating due to the need for barrier film (up to 20% of the wire width) to prevent Cu from diffusing into the surrounding dielectric**

- **Theory and modeling problems concerning Cu metallization**
  it is necessary further development of microscopic discrete theory of vacancy and ion transport as well as deformation processes, atomistic description of conducting component structure

Публикации:

- **Т.М.Махвиладзе, М.Е.Сарычев.** Теория электромиграционной неустойчивости границы соединенных проводящих материалов // Труды Фтиан. 2018. Т.27. С.97-104.
- **Т.М. Махвиладзе, М.Е. Сарычев.** Теория электромиграционных отказов межсоединений с учетом диффузии френкелевских пар // Труды ФТИАН. 2019. Т.28. С.20-31.