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ELECTROMIGRATION-INDUCED DISLOCATION CLIMB AND MULTIPLICATION IN CONDUCTING LINES

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Abstract—Electromigration along dislocation cores is considered as a mass-transport mechanism, in conducting lines of bamboo-like grains, below one half of the melting temperature. Given that the dislocation density in annealed metals may be insufficient to account for the observed mass-transport rate, this paper focused on electromigration-induced dislocation motion and multiplication. A prismatic loop climbs like a rigid ring, as electromigration relocates atoms along the core, from one portion of the loop to the other. Each loop is therefore a mass carrier: a vacancy loop migrates towards the cathode and an interstitial loop towards the anode. Furthermore, a thread of an edge dislocation multiplies prismatic loops under a sufficiently high electric field. A bamboo grain-boundary catches loops on one side and emits on the other. Available empirical facts are discussed according to this picture, including lifetime, linewidth, stress gradient and alloying.

1. INTRODUCTION

Solid diffusion driven by electric current, known as electromigration, has been a persistent challenge to the electronics industry ever since it was identified in aluminum films in the 1960's [1–3]. When an electric current passes a metal line, the ions are subjected to two forces resulting from, respectively, the electrostatic field and the electron collision. They are in opposite directions. For aluminum, the electron collision prevails so that the ions diffuse in the direction of the electron flow. Voids and hillocks form where mater depletes and accumulates, respectively. The conductor fails when the voids grow across the width of the line, or the hillocks connect with the adjacent lines. The aluminum lines operate in integrated circuits below 500 K, so that grain-boundary diffusion dominates over lattice diffusion. Free surface diffusion is also believed to be unimportant because aluminum readily forms oxide coating. Intense research in the 1970's led to strategies to increase electromigration resistence. For example, aluminum alloyed with a few percent of copper has about 80 times the lifetime of pure aluminum [1, 2]. Lifetime is also prolonged by eliminating grain boundaries along the current direction, such as in narrow lines with bamboo-like grains [4].

The impetus for more recent research comes from further downscaling of integrated circuits [3]. Concepts developed for wide lines must be reexamined. One issue that has caused much controversy concerns narrow lines of bamboo grains. The grain boundaries no longer connect into a network, so they do not by themselves facilitate long-range diffusion. Yet the bamboo lines still fail by voids, indicating long-range matter relocation. Perhaps the most striking observation is that many fatal voids form inside grains instead of at grain boundaries [5, 6]. Migrating cavities have been proposed as a mass-transport mechanism through the grains, which is due solely to electromigration on the cavity surface [7, 8]. The mechanism may operate provided the cavities preexist and are large enough to break away from the grain boundaries, such as in lines subjected to thermal stresses prior to electromigration test [9]. It is unlikely that the mechanism would account for hillocks formed in conducting lines without passivation.

Dislocations facilitate diffusion like pipes joining the bamboo grain-boundaries. To be effective, high dislocation density is required. The diffusivities of grain boundaries and dislocation cores are correlated as $D_c A_c \approx D_b \delta_b^2$, where A_c is the dislocation-core area and δ_b the grain-boundary thickness. Consequently, the effective diffusivity due to the both is

$$D_{\text{eff}} = \frac{D_b \delta_b}{d}\left(1 + \frac{\delta_b d}{L^2}\right) \tag{1}$$

where d is the grain diameter and L the dislocation spacing, with L^{-2} being the dislocation density. The relative significance of the two diffusion paths does not vary much with the temperature owing to the similar activation energies, but does vary with the grain diameter and dislocation spacing. Taking $d = 3 \times 10^{-6}$ m, $\delta_b = 3 \times 10^{-10}$ m and $L = 10^{-7}$ m, the second term in the bracket is about 0.1. That is, the grain boundaries transfer matter about ten times faster than the dislocation cores. Thus, a bamboo line is expected to have about 10 times the lifetime of a wide film, which is broadly consistent with experimental data [4].

It remains unclear, however, whether dislocations aligned in the current direction are as closely spaced as assumed above ($L = 0.1\ \mu$m). Dislocation spacing typically exceeds 1 μm in annealed bulk metals. In aluminum films, dislocations can be generated by thermal stresses during film preparation: spacing ranging $L = 0.1$–$0.7\ \mu$m is reported under various anneal conditions [10]. In this paper, dislocation *migration* and *multiplication* induced by electric current are considered. A prismatic loop moves under an electric field as atoms diffuse along the core from one portion of the loop to the other. The loop therefore acts as a *mass-carrier* driven by the electric field. Furthermore, prismatic loops can multiply from a thread of edge dislocation. The entire process is facilitated by electromigration along dislocation cores and perhaps grain-boundaries. Neither lattice nor grain-boundaries need to donate vacancies. The mechanism may dominate in well-annealed metals at low temperatures, where other mechanisms are suppressed. The process will be described in detail following the relevant dislocation mechanics.

2. DISLOCATION CORE DIFFUSION

Lattice and grain-boundary electromigration have been thoroughly investigated [1, 3]. The essential idea carries over to dislocation core—that is, the electron wind, by collision, exerts a force on each ion in the core

$$F_e = -ZeE_t \tag{2}$$

where $Z(>0)$ is the effective valence of each ion, e the magnitude of the electron charge, and E_t the electric field component tangent to the dislocation line. For aluminum, the ions diffuse in the direction of the electron flow; thus the negative sign. Theoretical work on electromigration falls into two types, either to calculate Z from atomic considerations, or to study phenomena above nanoscopic scale. This work belongs to the latter.

In addition to the electron-wind, other forces also drive core diffusion. Of significance to this work is the dislocation line tension γ_D, and the stress component in the direction of the Burgers vector σ_n, giving chemical potential [11]

$$\mu = -\kappa\gamma_D\Omega/b - \Omega\sigma_n \tag{3}$$

where b is the Burgers vector and κ is the curvature (positive for a circular vacancy loop). In this paper, a constant line tension $\gamma_D = \alpha Gb^2$ will be adopted, G being the shear modulus and α a numerical factor. A value $\alpha = 0.5$ will be used in calculations.

The total force on each ion is

$$F = -ZeE_t - d\mu/dl \tag{4}$$

with l being the distance along the dislocation line. The atomic flux J—the number of atoms per unit time passing a cross-section of the core—is related to the force by

$$J = \frac{D_c A_c}{\Omega kT} F \tag{5}$$

where $D_c A_c$ is the effective core diffusivity, Ω the volume per atom, kT the usual kinetic energy unit. Listed in Table 1 are the data for pure aluminum. Note that values of $Z = 1$–100 are used by various authors for grain boundaries, and the diffusivity may have a similar degree of uncertainty at any given temperature. Electric field E is used in this paper; electric current density j is converted by $E = \rho j$.

3. CLIMBING LOOPS AS MASS CARRIERS

Climb normally requires vacancies to diffuse between dislocations and lattice. Yet climb solely by core diffusion has also been observed. A well-known microscopy observation involves a prismatic loop, migrating with invariable size, under the stress gradient set by a nearby straight dislocation [13]. Core diffusion relocates atoms from one portion of the loop to another, leading to the loop to migrate like a rigid disk. Although very instructive, the phenomenon has been thought unimportant to creep because it does not operate under macroscopically applied stress. However, the loops can migrate under a uniform electric current. Furthermore, they are *mass carriers*: each prismatic loop carries a disk of either vacancies or interstitials. The loops can form during film preparation [10], or after the electric field is applied. The latter process will be discussed in the next section. In this section the electron-wind force and drift velocity are computed for loops of arbitrary shape. Only vacancy loops will be analyzed; results for interstitial loops are the same but for the sign.

Figure 1 illustrates a prismatic loop lying on the surface of an imaginary cylinder whose axis coincides with the Burgers vector. A segment of the loop may *glide* on, and *climb* normal to, the surface of the cylinder. It is convenient to think that the cylinder deforms and translates with the loop. The projection of the dislocation on the cylinder base defines the

Table 1. Material data for pure aluminum

Burgers vector	$b = 2.86 \times 10^{-10}$ m
Atomic volume	$\Omega = 1.66 \times 10^{-29}$ m^3
Resistivity	$\rho = 2.69 \times 10^{-8}$ Ωm
Shear modulus	$G = 2.54 \times 10^{10}$ N/m^2
Core diffusivity [12]	$D_c A_c = 7.0 \times 10^{-25} \exp(-1.4 \times 10^{-19}\ \mathrm{J}/kT)$ m^4/s
Effective valence	$Z = 20$

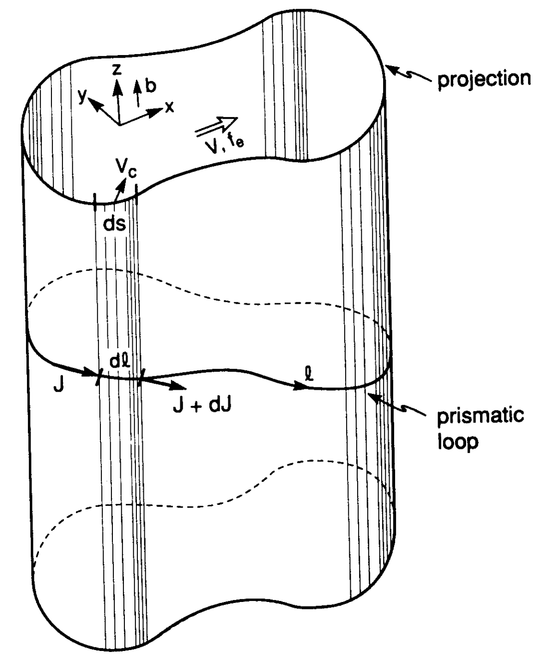

Fig. 1. A vacancy loop lying on an imaginary cylinder whose axis coincides with the Burgers vector.

edge of the "extra atomic plane", which lies outside the vacancy loop in Fig. 1. The dislocation and its projection may change shape, but the area enclosed by the projection is invariant because the vacancies are confined to move along the dislocation core. Lattice diffusion is ignored at the temperatures of interest.

3.1. Electron-wind force on a prismatic loop

The electron wind exerts a net force on a prismatic loop as a whole, denoted as f_e. In equilibrium when the loop is immobile, f_e is balanced by actions other than the electric field, e.g. the drag of a precipitate. The force is normal to the Burgers vector, because electromigration does not cause the loop to glide. A general formula can be derived by invoking virtual work arguments. Imagine that the loop undergoes a virtual translation like a rigid body, at virtual velocity V normal to the Burgers vector. A coordinate system is shown in Fig. 1, where the velocity coincides with the x-axis and the Burgers vector with the z-axis. Balance of virtual work rate at the equilibrium requires that

$$\oint F_e J \, dl = f_e V. \tag{6}$$

The integral is evaluated over the dislocation loop. The virtual flux J needs not to relate to F_e through diffusivity, but must be compatible with the virtual velocity V. The relation between J and V is derived as follows.

Focus on an element of the dislocation dl and its projection on the cylinder base ds. The number of atoms flowing out of dl per unit time is dJ. Let V_c be the velocity of the dislocation climb, normal to the cylinder, positive if the vacancy loop shrinks. The climb adds $V_c b \, ds/\Omega$ atoms per unit time. Mass conservation requires that the atoms flowing into dl extend the edge of the extra-atomic-plane. Thus

$$dJ + V_c b \, ds/\Omega = 0. \tag{7}$$

The loop translates at velocity V in the x direction and therefore $V_c \, ds = -V \, dy$. Equation (7) becomes

$$dJ/dy = Vb/\Omega. \tag{8}$$

Integrating one obtains that

$$J = (Vb/\Omega)y + C. \tag{9}$$

The integration constant C signifies the circulation around the loop. Note that (7) applies even when the dislocation changes its shape, but (9) applies only when the dislocation translates like a rigid body. The latter can also be derived directly from a finite segment translating along the x-axis. The compatibility equation connects either virtual or real pair of J and V.

The loop is subjected to a uniform electric field $\mathbf{E} = \{E_x, E_y, E_z\}$; the component tangential to the dislocation line is $E_t = \mathbf{E} \cdot d\mathbf{l}/dl$. Substituting (2) and (9) into (6), one obtains that

$$f_e = Ze(E_x S_z - E_z S_x)b/\Omega \tag{10}$$

where S_x and S_z are the areas enclosed by the projections of the dislocation in the x and z directions, respectively. Note that Stoke's theorem is used in integrating (6). In summary, under a uniform electric field $\mathbf{E}$, a loop with the Burgers vector $\mathbf{b}$ is subjected to a net force f_e which lies in the plane spanned by $\mathbf{E}$ and $\mathbf{b}$, directed normal to $\mathbf{b}$.

Consider special cases of planar loops of arbitrary shape (Fig. 2). The electric field component normal to the loop-plane does not drive diffusion and is therefore ignored. Figure 2(a) illustrates a vacancy loop with the Burgers vector normal to its plane. The net force on the loop specialized from (10) is

$$f_e = ZeESb/\Omega \tag{11}$$

where S is the area enclosed by the loop. For conservative climb, the shape of the loop may change under various forces, but not the enclosed area S. Consequently, *the electron-wind force on the planar loop is independent of the presence of other forces.*

Figure 2(b) illustrates a glide loop subjected to an electric field along the Burgers vector. An inspection shows that the core diffusion causes the loop to *climb off* its plane, in the direction indicated. The magnitude of the electron-wind force on the loop is still given by (11). Figure 2(c) illustrates a glide loop subjected to an electric field normal to the Burgers vector. The loop may twist under the electric field but cannot translate like a rigid body.

3.2. Drift velocity of a prismatic loop

First consider a circular vacancy loop of radius R lying in the plane normal to the Burgers vector [Fig. 2(a)]. The circular shape is assumed to be in equilibrium in the absence of electric field—that is, the chemical potential due to various other forces is constant along the loop. It will be shown that such a circular loop translates like a rigid disk under a uniform electric field.

The component of the electric field along the dislocation line is $E_t = -Ey/R$ for the circular loop in Fig. 2(a). Only the electron wind drives diffusion when the loop remains circular, so that the flux is

$$J = \frac{D_c A_c}{\Omega kT} ZeEy/R. \tag{12}$$

Owing to symmetry, $J = 0$ at $y = 0$, so that $C = 0$ in (9). Equations (9) and (12) are consistent provided the drift velocity is identified

$$V = \frac{D_c A_c}{kTRb} ZeE. \tag{13}$$

The velocity is proportional to the electric field and inversely proportional to the loop radius. At temperature $T = 500$ K and electric field $E = 1$ kV/m, a loop of radius $R = 0.1\ \mu$m translates at velocity $V = 1.8 \times 10^{-11}$ m/s. For the case in Fig. 2(b) the magnitude of the climb velocity is still given by (13).

Now consider a loop of arbitrary shape which may change when the electric field is applied. Suppose that the loop attains a steady-state, i.e. translates with a fixed shape, after the electric field is turned on for some time. Equating (9) and (5) leads to

$$\frac{Vb}{\Omega} y + C = \frac{D_c A_c}{\Omega kT} (F_e + F_{self}). \tag{14}$$

The force on each atom is divided into electron-wind force and the self-force induced by the line tension or stress of one segment on another. The self-force does not exert any net force on the loop as a whole. According to (9), $J = y$ is a virtual flux compatible with rigid translation. Consequently, integral $\oint y F_{self}\, dl$ scales with the net force on the loop due to the self-force, which must vanish. Equation (14) times y integrated over the loop leads to

$$V = Ze \frac{D_c A_c}{kTb} \frac{E_x S_z - E_z S_x}{\oint y^2\, dl}. \tag{15}$$

Note that the integral in (15) varies with the shape of the loop, which in turn is determined by the electron-wind force and various self-forces. Judging from (15) one may use the simple relation (13) liberally for loops of arbitrary shape, interpreting R as a characteristic size of the loops.

4. MULTIPLYING DISLOCATIONS UNDER ELECTRIC FIELD

Dislocation density in annealed aluminum films may be insufficient to account for the observed mass-transport rate. In this section, mechanisms of multiplying dislocations under electric field are considered. Dislocations climb via core diffusion. Vacancies are supplied from other dislocations, grain boundaries, or cavities formed during film preparation. Whether a dislocation can bow out from its pinning points depends on the competition between the electron-wind and the line tension. A nondimensional group governing the instability will be identified.

4.1. Dislocation buckling in the electron wind

No force drives diffusion along a straight edge dislocation lying perpendicular to the electric field. Yet diffusion turns on if the dislocation bends slightly. The electric field tends to further bend the dislocation, and the line tension to straighten it. Above a critical electric field, the dislocation buckles into sinusoidal configurations. the condition is rigorously analyzed as follows.

Figure 3 illustrates two dislocations pinned at A and B by other dislocations or grain boundaries. In each case, the extra-atomic-plane lies in the plane of the paper, above the segment. A profile $p(x)$ is maintained in equilibrium by the electric field E and the line tension. For small bending, $|p|/L \ll 1$, the tangential component of the electric field is $E_t = Ep'$, and the curvature is $\kappa = -p''$. Using (4) the equilibrium requires that

$$\alpha G b \Omega p'''(x) + ZeEp'(x) = 0. \tag{16}$$

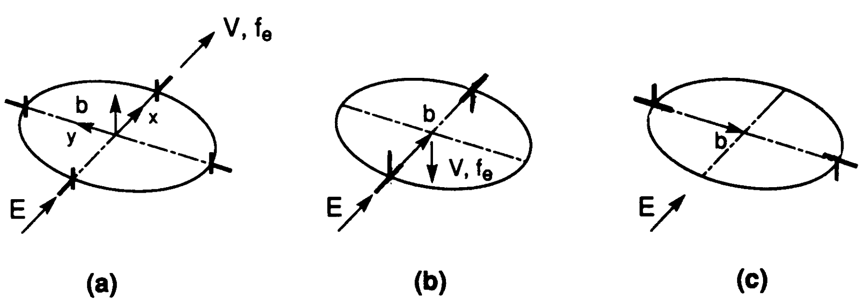

Fig. 2. Planner loops. (a) A vacancy loop. (b) A glide loop under electric field parallel to the Burgers vector. (c) A glide loop under electric field normal to the Burgers.

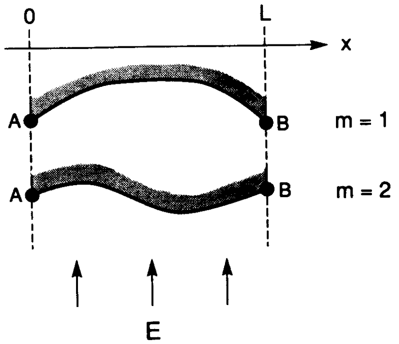

Fig. 3. A straight dislocation buckles when the electric field exceeds a critical value. The extra-atomic-plane lies in the plane of the paper above the segments (shaded). Mode $m = 1$ pumps atoms from the dislocation into the ends; Mode $m = 2$ conserves mass by relocating atoms from the receding edge to the extending edge.

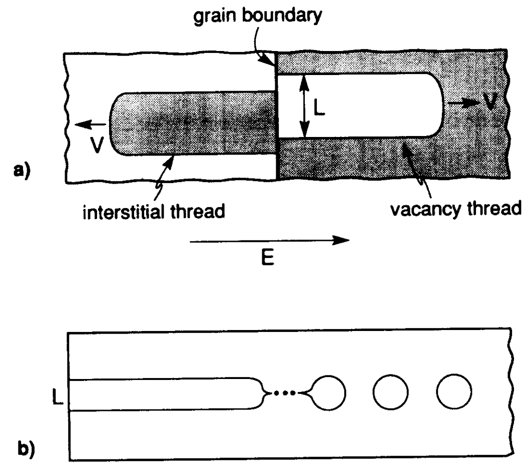

Fig. 4. (a) Two dislocation threads climbing away from a grain boundary. (b) A long thread blows out loops.

The ordinary differential equation is solved by

$$p(x) = A\,\sin\left(\sqrt{\frac{ZeE}{\alpha Gb\Omega}}\,x\right) + B\,\cos\left(\sqrt{\frac{ZeE}{\alpha Gb\Omega}}\,x\right) + C \qquad (17)$$

where A, B and C are undetermined constants. Ignore the rigid translation, i.e. $C = 0$. The dislocation is pinned at the two ends so that $p(0) = p(L) = 0$. Nontrivial solution exists only if the electric field takes the eigenvalues given by

$$\frac{ZeE_{\mathrm{m}}}{\alpha Gb\Omega}L^2 = m^2\pi^2 \qquad (18)$$

where m is any positive integer. The first two modes of the equilibrium profile are illustrated in Fig. 3. Mode $m = 1$ requires a net flow of atoms from the segment into ends A and B. Mode $m = 2$ conserves mass: atoms flow from one portion of the segment to the other, but not into or out of ends A and B.

Although the post-buckling motion has not been analyzed, it is reasonable to expect that an electric field of magnitude similar to E_{m} will cause the segment to bow out from the pinning points A and B. Notice that the product $E_{\mathrm{m}}L^2$ equals a constant specific to material. For pure aluminum, the first mode gives

$$E_1L^2 = 1.8 \times 10^{-10}\mathrm{Vm}. \qquad (19)$$

For a segment of length $L = 1\ \mu$m, the critical field to bow out the first mode is $E_1 = 180\ \mathrm{V/m^2}$. Uncertainty of (18) arises from the effective valance and line tension; a larger Z or a smaller α would reduce the critical electric field. The critical electric field also changes for a segment which has already bent substantially.

4.2. Threading dislocations and blowout loops

Post-buckling motion extends the length of the edge dislocation and thereby transports matter. Only the first mode will be considered in the following. Figure 4(a) illustrates a particular situation where two edge dislocation threads extend in opposite directions from a grain boundary. The extra-atomic-plane for each thread is shaded; the two dislocations will be referred to as interstitial and vacancy thread, respectively. With this arrangement, the grain boundary does not donate or accept vacancies, but facilitates vacancies to diffuse from the interstitial thread to the vacancy thread. The vacancy and the interstitial thread extend at the same velocity, so that the mass-transport mechanism can lead to both voids and hillocks. If the grain-boundary diffusion is fast, the flux along the dislocation near the ends of the threads is driven by the electron wind alone. Consequently, the velocity at the threading front is given by (13) with $R = L/2$.

A long thread loses stability again: it blows our a prismatic loop [Fig. 4(b)]. The process repeats itself as the loop drift away. The instability can be understood by considering two straight edge dislocations

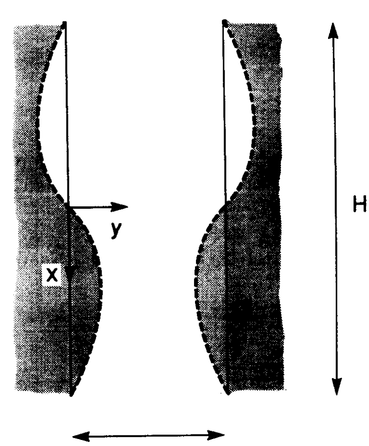

Fig. 5. Buckling of two interacting edge dislocations. The extra-atomic-plane is shaded for each dislocation.

placed in the vicinity of each other (Fig. 5). One dislocation exerts on the other a tensile stress normal to the plane [11].

$$\sigma_n = \frac{Gb}{2\pi(1-v)y} \quad (20)$$

where v is Poisson's ratio. According to (4), the gradient $\partial\sigma_n/\partial y$ plays the same role as the electric field, driving atoms to diffuse from one portion of a dislocation to another, in the direction that further bends the dislocation. The dislocation buckles when the stress gradient prevails over the line tension. Making the following substitutions in (18)

$$ZeE \to \Omega\, \partial\sigma_n/\partial y, \quad L \to H \quad (21)$$

one finds that the critical length H is given by

$$H/L = 2\sqrt{\pi^3(1-v)} \approx 9. \quad (22)$$

Owing to the different conditions at the ends, the critical length for a thread to blow out a loop differs from that predicted by (22).

The multiplication mechanism resembles that of Bardeen and Herring [14] in that both require dislocations to climb. But the differences are significant. The Bardeen–Herring loops grow by accepting vacancies from the lattice so that lattice diffusion dictates the rate. The mechanism described here requires dislocation-core and grain-boundary diffusion, and operates under electric current. Furthermore, vacancy and interstitial loops can multiply simultaneously, which subsequently drift in opposite directions. Neither lattice nor grain boundaries need to donate net vacancies. Of course, the process accelerates if vacancies or cavities exist in the grain boundaries prior to electromigration tests.

5. DISCUSSION

This writer is unaware of any direct observation of electromigration-induced dislocation climb or multiplication. The closest observation is conservative climb of prismatic loops driven by a stress gradient [13]. The electromigration-induced climb described here should not be confused with the motion of charged dislocations in ionic crystals. Among the differences, the latter is due to electrostatic interaction and the charged dislocation can *glide* under the electric field [11]. At this stage, the consequences of electromigration-induced disloation climb can be discussed in conjunction with the available empiricial facts. Some indirectly support the theory; others call for further research.

5.1. Lifetime

Temperatures 400–500 K and electric fields 100–1000 V/m are used to accelerate electromigration tests. The lifetime under operation conditions is extrapolated using empirical formula [1–3]

$$t_f \propto E^{-n} \exp(Q/kT). \quad (23)$$

Experimental data show that $n \approx 2$, and Q is close to the activation energy of grain-boundary diffusion, which also makes it close to that of dislocation-core diffusion.

Void growth in a narrow conducting line requires two processes. First, vacancies diffuse over a distance larger than the linewidth and accumulate in front of a barrier. Second, the accumulated vacancies froim a large void by diffusing over distance shorter than the linewidth. The first process is predominantly driven by the applied electric field, and the second by surface energy and stress. It is usually assumed that the lifetime is primarily consumed by the first process—that is, a conducting line fails when, or soon after, sufficient vacancies accumulate at a diffusion-barrier. For example, diffusion driven concurrently by electromigration and vacancy-concentration gradient is analyzed, which gives the field exponent $n = 2$ for the predicted lifetime [15]. The calculation assumes an effective diffusivity and therefore applies to dislocation-core diffusion, provided the combined diffusivity (1) is used.

Although the short-range diffusion in the second process takes little time by itself, the details of the process may significantly affect the lifetime, for they dictate how many vacancies need be transported by the long-range diffusion to fail the line. For example, both narrow slits and rounded voids have been observed, which require different amount of vacancy transfer and thereby give different lifetimes. This subtlety aside, identifying long-range mass-transfer mechanisms would be a prerequisite for any models to predict the lifetime.

An additional perspective can be offered when core diffusion operates alone. The average number of atoms per unit area per unit time passing a metal line is

$$J_{av} = \frac{D_c A_c}{kTL^2} ZeE \quad (24)$$

where L is the dislocation spacing, i.e. L^{-2} is the dislocation density. Because dislocations multiply under the electric field, L decreases and thereby J_{av} increases, until the conducting line is so crowded that dislocations can no longer multiply. For a given electric field E, the minimum dislocation spacing is governed by (18), i.e.

$$L^{-2} = \beta \frac{ZeE}{\Omega Gb} \quad (25)$$

where β is a dimensionless number. A combination of (24) and (25) shows that the steady-state atomic flux scales as

$$J_{av} \propto E^2 \exp(-Q/kT). \quad (26)$$

The lifetime is inversely proportional to the steady-state atomic flux, $t_f \propto 1/J_{av}$. The empirical formula (23) is therefore accounted for by dislocation multiplication with $n = 2$.

5.2. Linewidth

For narrow lines (width $< 2\,\mu$m), the lifetime is known to increase as the linewidth decreases [3, 4]. A prevailing explanation holds that narrow lines decrease the number of the longitudinal grain-boundaries [16–18]. On the basis of the present theory, an additional explanation becomes possible. According to the instability condition (19), for a given electric field, a critical linewidth exists, below which dislocations cannot multiply. Consequently, diffusion is facilitated by dislocations left after annealing. This mechanism predicts that even for pure bamboo-lines the lifetime increases with decreasing linewidth. None of the previous theories predicts this effect.

5.3. Stress gradient

A stress gradient sets up as atoms diffuse, exerting on atoms a driving force opposite to the electron-wind [19–21]. The electromigration-induced stress gradient is therefore believed to be beneficial. The stress gradient can be increased with a passivation coating which constains plastic flow, or closely spaced diffusion-barriers which build up stresses over a short distance. These observations are consistent with both grain-boundary and dislocation-core diffusion. When a stress gradient $\nabla\sigma_n$ exists in addition to the electric field E, the velocity for a drifting loop (13) should be modified by

$$V = \frac{D_c A_c}{kTRb}(ZeE - \Omega\nabla\sigma_n). \tag{27}$$

As mass transports and the stress gradient builds up, the drifting velocity decreases.

5.4. Alloying

It was discovered in the 1970's that aluminum alloyed with a few percent of Cu, Mg and Cr, individually or in combination, has lifetime about two orders of magnitude longer than pure aluminum. Furthermore, a correlation was found that many creep-strengthening alloys are also electromigration-strengthening. Yet it remains controversial whether the creep-strengthening theories apply to electromigration [22, 23]. Particles of Al_2Cu form in thin films following the same sequence observed in bulk Al(Cu) alloys. The metastable, semi-coherent particles (θ' phase) are detrimental to electromigration resistence. The stable, incoherent particles (θ phase) coarsen by consuming the metastable particles and one another. The coarsening is accelerated by the electric field. See Ref. [23] for a detailed account. Discussed in the following are effects of the precipitates on electromigration lifetime.

Take two limiting cases where the size of the loops is either much larger or much smaller than that of the precipitates. Figure 6 illustrates the former, a vacancy loop interacting with a small precipitate. The electron-wind force on the loop is given by (11), and the precipitate drags the loop by line tension, $2\gamma_D$. The

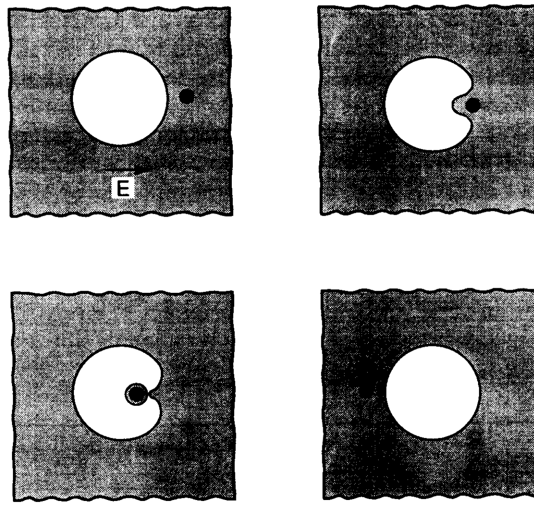

Fig. 6. Under an electric field, a vacancy loop first engulfs a small precipitate, and then breaks away from it.

loop breaks away from the precipitate if the electron-wind prevails, i.e.

$$\frac{ZeER^2}{\alpha bG\Omega} > \frac{2}{\pi}. \tag{28}$$

Note this dimensionless group is similar to that governing instability (18). The right-hand side of (28) will amplify by factor N if the loop encounters N precipitates simultaneously. Judged from (28), dispersed precipitates should be effective in stopping dislocation motion and multiplication. However, the loop, *climbing* towards the precipitate, may *glide* over the precipitate. The mechanics problem has not been analyzed to ascertain the additional degree of freedom. Should the glide-assisted climb operate, the dispersed precipitates would be ineffective in stopping loop motion and multiplication. Also affecting is that the small precipitates themselves migrate under the electric field.

Precipitates may play a much more important role when they become large enough to almost block the line. Suppose they form periodic diffusion-barriers, of spacing l, along the narrow conducting line (Fig. 7). As vacancies and atoms accumulate at the barriers, a stress gradient sets up which decelerates diffusion. Diffusion fully arrests if [16, 19]

$$ZeE < 2\sigma_B\Omega/l \tag{29}$$

where σ_B is the stress that can be sustained by the metal near the barrier, which should be on the order

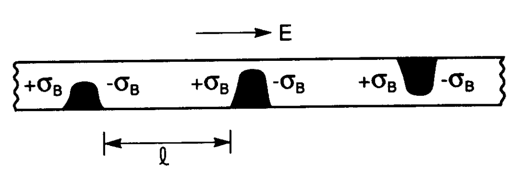

Fig. 7. Large precipitates serve as diffusion-barriers which build up stress gradient to decelerate diffusion.

of the yield stress. For $E = 350$ V/m and $\sigma_B = 10^8$ Pa, the needed barrier spacing is $l = 3\ \mu$m.

The above analysis assumes that the barriers themselves are immobile. Yet it has long been known that the precipitates migrate under electric current. In fact, each precipitate now is subjected to both electric field and stress gradient, which tend to move the precipitate in the *same* direction, towards the anode. Diffusion of copper along the precipitate/matrix interface may facilitate the precipitate migration. It can be shown that a small precipitate migrates faster than a large one [24]. Such migration accounts for the accelerated coarsening in electromigration tests. When the precipitates are too far apart, the stress gradient between them drops and becomes insufficient to arrest diffusion. The conducting line fails soon after.

If this picture is correct, the precipitates should be conditioned at high temperatures to be large enough to act like diffusion barriers, but still sufficiently closely spaced to retain the stress gradient. Further coarsening at the operation temperature and electric field must be prevented. The recent experimental observations of Kim and Morris [23] may be interpreted this way. Observe that the precipitates here are not incorporated to increase creep strength, but to form an array of diffusion-barriers.

5.5. Electromigration-induced dislocation climb

Electromigration-induced dislocation climb has been considered up to now as a damage mechanism posing a challenge. Yet viewed from a different perspective, the very phenomenon can be an opportunity to study certain basic aspects of dislocation motion. A prismatic loop can be used as a diffusion marker. Both velocity and direction of the migration can be controlled by electric field. Using (13), one can determine $D_c A_c Z$ by drifting velocity measured by electron microscope observations. Furthermore, Z may be independently measured from any one of the instabilities described in this paper. As an example, consider the interaction between a prismatic loop and a precipitate (Fig. 6). A needle-shaped particle may be needed to avoid gliding over the particle. For a sufficiently high electric field the loop will first engulf the precipitate, and then break away from it. This would give a lower bound to Z from (28). The precipitate will be outside the loop again if an electric field in the opposite direction is applied. The experiment can then be repeated with a lower electric field.

6. CONCLUDING REMARKS

Electromigration-induced dislocation climb is proposed as a mass-transport mechanism that damages conducting lines of bamboo grains at low temperatures (the room temperature up to about 200°C for aluminum). Consequences of this theory are explored. A prismatic loop is a mass-carrier under electric field, drifting by conservative climb. Competition between electron wind and line tension leads to a critical value of EL^2, above which an edge thread multiplies prismatic loops, where E is the electric field and L the spacing between the dislocation-pinning points. Electric field may be used as an additional means to control dislocation motion, suggesting opportunities for basic investigations. Although conservative climb has been observed under internal stress gradient, the writer is unaware of any direct observation of dislocation climb in metals under electric current. It is imperative to conduct microscopy observations of these loops under electric field.

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