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SECOND WORKSHOP ON SCIENCE AND TECHNOLOGY OF THIN FILMS

(11 - 29 March 1996)

" 1/f noise as a tool to characterize thin films"
"Noise as a useful physical quantity"

presented by:

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1/f Noise as a tool to characterize thin films

Noise as an useful physical Quantity

- The concept of 1/f noise.
- 1/f noise as distinct from other types of noise.
  Other noise e.g, Thermal Noise
- How to measure the 1/f noise (a schematic set up)
- 1/f noise as a "probe " of atomic motion in the solid.
- Two examples :

1. **Metallic films** - the problem of electromigration

   and reliability of metallic interconnects.

2. **Metallic Oxide films** - role of oxygen motion .

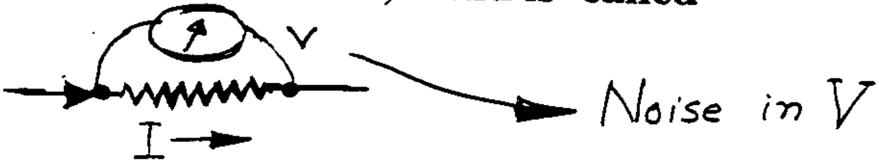
Use of electrical noise as a probe to characterise thin films

In general electrical noise is something that we want to minimise in our experiments.

But , there are certain "useful noise" which contains information about the microscopic physical processes taking place in the solid.

→ "Foot prints" of microscopic processes

One such useful noise is the " conductivity noise"
This is the noise when an electrical current passes through a conductor . This noise often has a frequency dependence which varies a $1/f^{\alpha}$ ($\alpha \approx 0.8$ -1.2) and is called "1/f noise".



→ Physics : Conductivity noise contains information about the diffusive atomic motion in a solid.

→ Application: Can this information be used to predict the approximate "life time" of a thin metallic interconnect ?

How long a metallic interconnect will last before it breaks down ?
Can Noise measurement provide an answer?

Noise :

(1) **Thermal Noise** known as **Johnson noise** or **Nyquist** noise . (even when there is no current flowing in a solid the noise is present.) In a solid of resistance R kept at a temperature T : $\Delta V = V - V_{DC}$

$< (\Delta v) >^2 = 4k_B T R \ (\Delta f)$. Δf = Band width !

~~End of Formula~~

This depends only on R and T but not on the microscopic details of the solid.

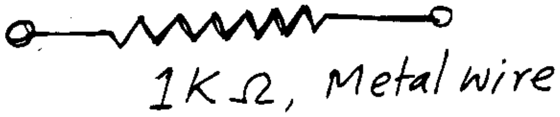
(2) Excess noise or conductivity noise (arises only when a current flows through a solid) Noise made visible

Extremely sensitive to the microscopic details of the electron conduction in the solid.

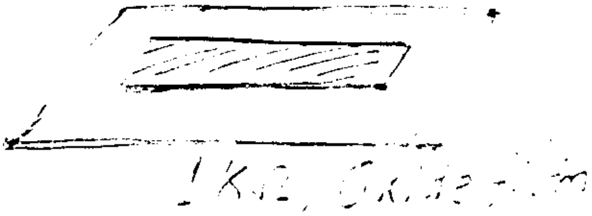
$$\langle (\Delta V)^2 \rangle = 4k_B T R (\Delta f) + \langle \Delta V^2 (I,f) \rangle \xrightarrow[\text{when } I=0]{} 0$$

Important

Two solids (e.g., an oxide resistor and a metal film resistor) with the same R kept at the same temperature will have the same Johnson noise. But can have very different conductivity noise.



Same Thermal noise



Different Excess noise

Noise Algebra

$V(t)$ is measured

$$\langle V(t)\rangle_{Avg.} \equiv V_{DC}$$

Power spectrum

Need Fourier transform of Voltage data

Definition :

power Spectrum $S_v(f) \equiv 4\int_0^\infty C_v(\tau)\cos(2\pi f\tau)d\tau$

$\downarrow$ Voltage Autocorrelation function

$$C_v(\tau) \equiv \langle V(\tau)V(0)\rangle - \langle V\rangle^2$$

(1) Thermal noise :

$$S_v(f) = 4k_BTR(f)$$

$R(f) \approx$ Constant

White Noise

(2) Conductivity noise :

$$S_v(f) \cong \underline{\gamma}\,\frac{V_{DC}^2}{\underline{\underline{N_c}}\,f^\alpha} \sim \frac{1}{f^\alpha} \quad \begin{bmatrix}\alpha \approx 0.8-1.2\\ \alpha \sim 1\end{bmatrix}$$

$\underline{\underline{\gamma}} \approx$ Constant for a System. $\underline{\underline{N_c}}$ = # of Charge Carriers

Certain important aspects of the "1/f noise" :

(a) Dependence on the measuring current

$$S_v(f) \propto V_{DC}^2 \propto I_{DC}^2$$

(b) Dependence on the volume

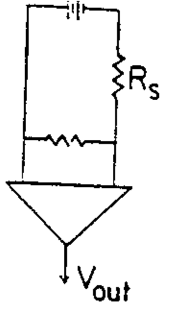
$$S_v(f) \propto N_c^{-1} \propto (\text{Volume})^{-1}$$

Normalised power spectrum :

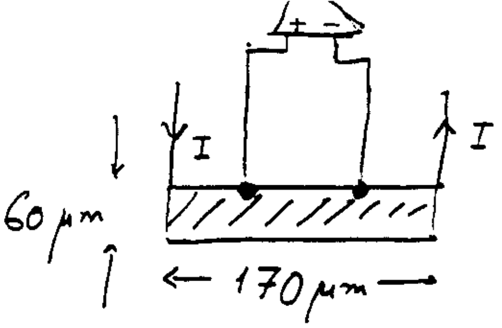
$$\frac{S_v(f)\times(\text{Volume})\times f^\alpha}{V_{DC}^2} \approx \frac{\gamma}{n_c}$$

n_c : Charge Carrier density

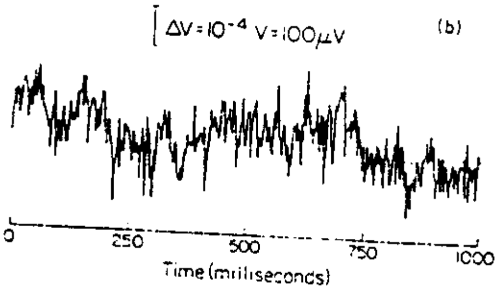
Helps to Compare different materials



(a)



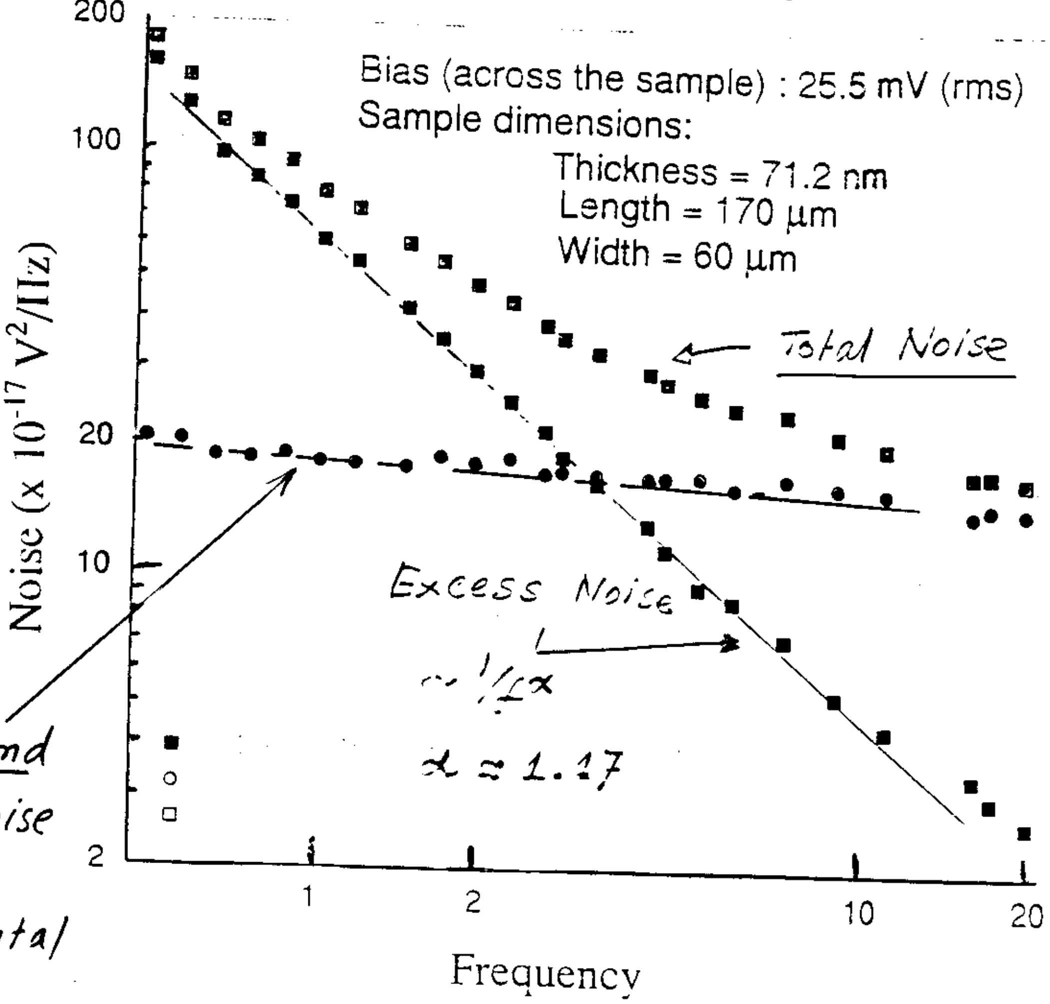
Bi film



→ v(t) →

Obtain power spectra of noise

Spectral density of noise for a thin Bi film



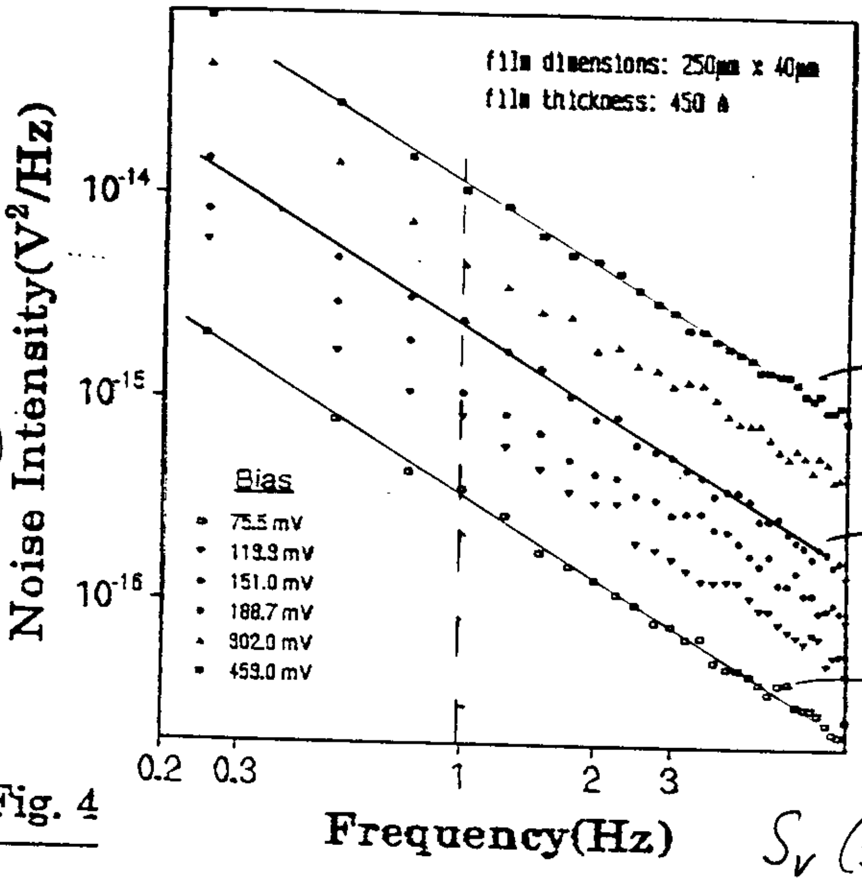
Back Ground
= Thermal noise
($4k_BTR$)
+ Instrumental

Excess Noise [illegible]

= Total noise − Background

Frequency dependance of Noise in a thin Bi film

250μm × 40μm
$t \approx 450$ Å
films



$S_v(f)$

V_{DC}

459.0mV

188.7mV

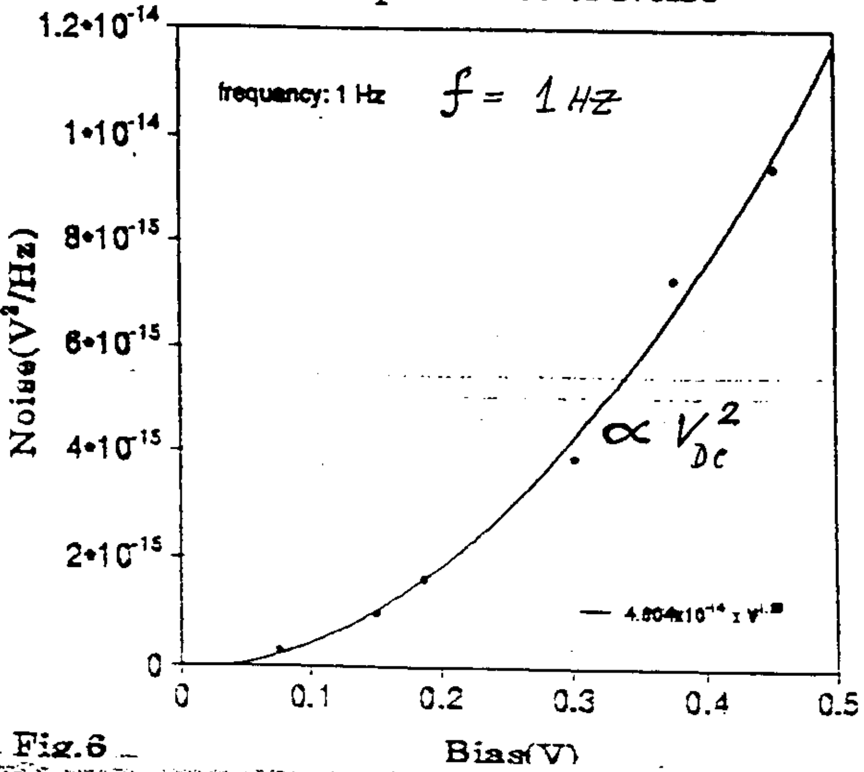
75.5mV

Fig. 4

$S_v(f) \propto \frac{1}{f^{\alpha}}$

Bias dependance of Noise

$S_v(f)$
$f = 1$ Hz



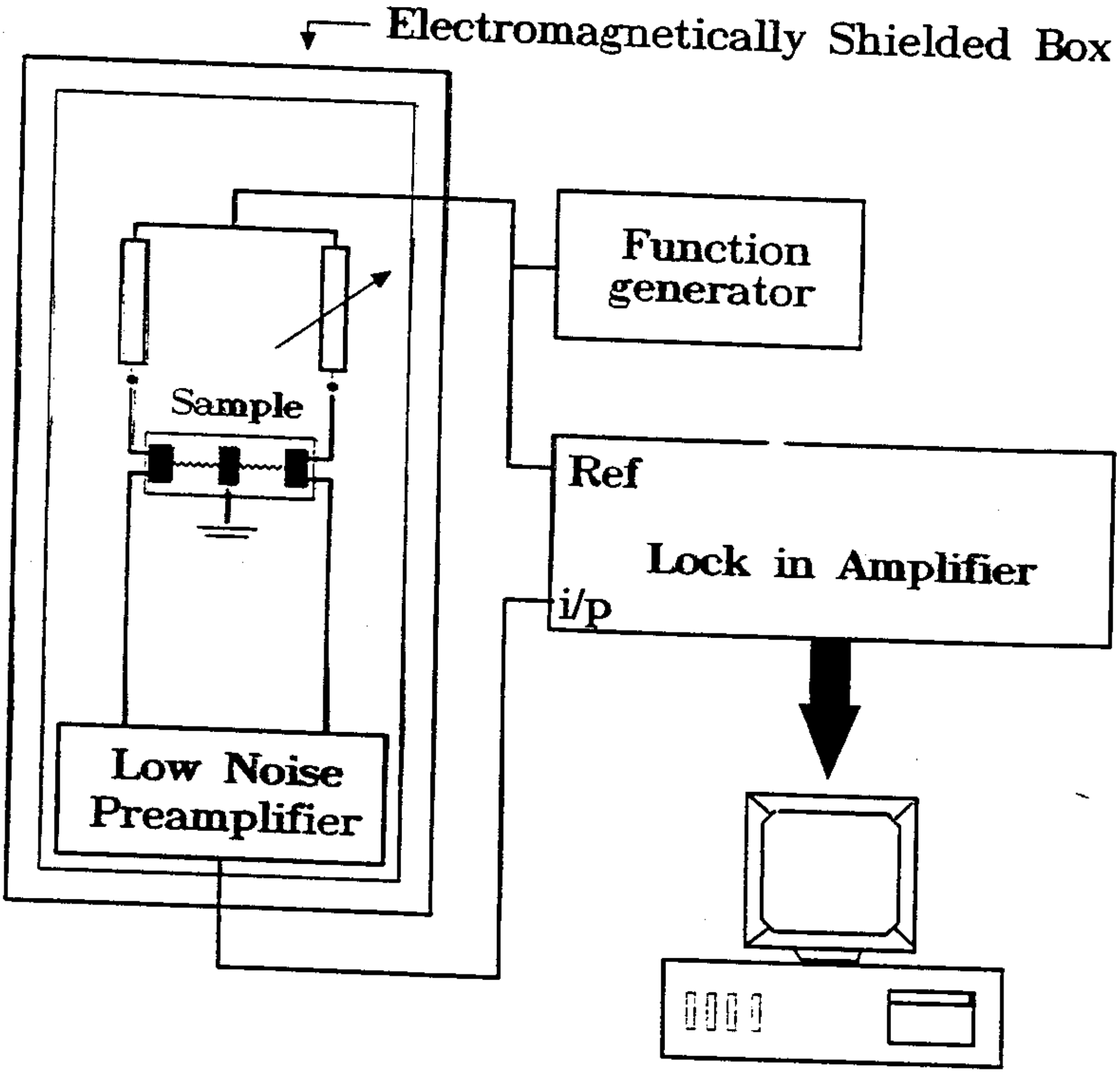
$S_v(f = 1 Hz)$
$\propto V_{DC}^2$

Fig.6

5 - Terminal Measurement

A.C technique, uses bridge balance

Ref: J. H. Scofield
Rev. Sci. Instr. 58, 985 (1987)



* Allows simultaneous measurement of total noise as well as background by a 2 phase measurement.

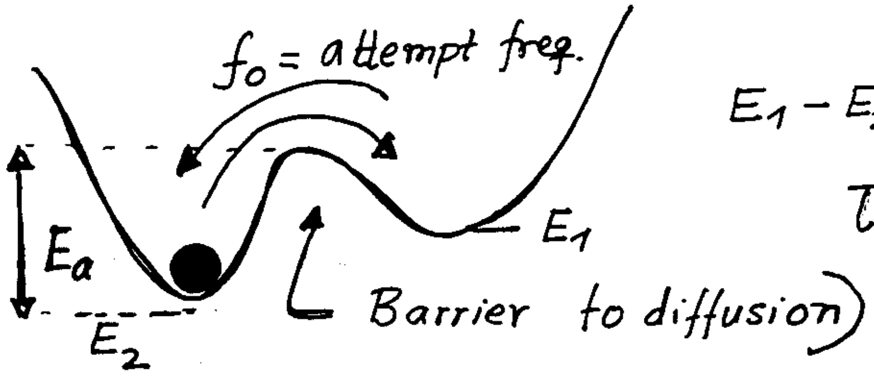
* Also minimizes instrumental 1/f noise.

Origin of 1/f noise in a solid (or any condensed matter) carrying a charge current

__One__ of the accepted **models** (i.e., one of the sources of the 1/f noise) is presence of smeared out activated kinetics .

"Dutta - Horn Model" Rev. Mod. Phys. (1981) } Good
Weissman Rev. Mod. Phys. (1988) } Review

Example: __Atomic diffusion with a broad distribution of the activation energy (E_a)__



$$E_1 - E_2 = \Delta E$$

$$\tau = \tau_0 \exp\left(\frac{E_a}{k_B T}\right)$$

$$2\pi\tau_0 = 1/f_0$$

Spectral density of occupancy fluctuation from one site =

$$S(f,T) = \mathrm{Sech}^2\left(\frac{\Delta E}{2k_B T}\right)\left(\frac{f_c}{f_c^2+f^2}\right)\Big/2\pi$$

$f_c \simeq$ characteristic frequency.

\+ Flat distitution of (E_1, E_2)

$$\hookrightarrow \boxed{S(f,T) \propto \frac{1}{f} \text{ dependence.}}$$

Other types of excess noise

For example :

Abrupt changes of the resistivity as a function of time.

May or may not have 1/f type power spectrum

Oscillations in the resistance at a fixed frequency (f_0)

Power spectrum will have dominant contribution at frequency f_0 .

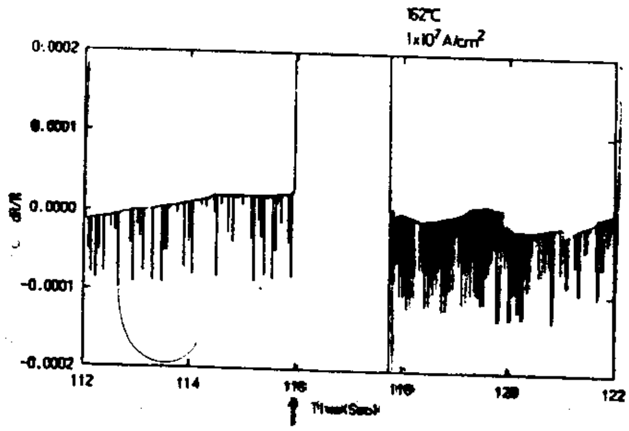


Fig.8 The behavior of the downward spikes when the current density was suddenly increased by 5%.

Note: A very high precision resistance jump measurements is also a potential tool

* Relation of 1/f noise with grain boundary diffusion

VOLUME 55, NUMBER 22 PHYSICAL REVIEW LETTERS 25 NOVEMBER 1985

1/f Noise and Grain-Boundary Diffusion in Aluminum and Aluminum Alloys

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(Received 24 April 1985)

Al
Al·Si(%)
Al-Cu(4%)
} used in IC interconnect

We have measured the 1/f noise in polycrystalline films of Al, Al-Si(1%), and Al-Cu(4%) in the temperature range of 300 to 600 K. The temperature dependence indicated activation energies of 0.69, 0.80, and 0.89 eV, respectively. These energies are similar to the activation energies found for Al diffusion along grain boundaries for films of the same size and composition measured in the same temperature range. Measurements of samples with identical compositions but differing widths and thicknesses revealed significant departures from the usual inverse volume dependence of the 1/f noise.

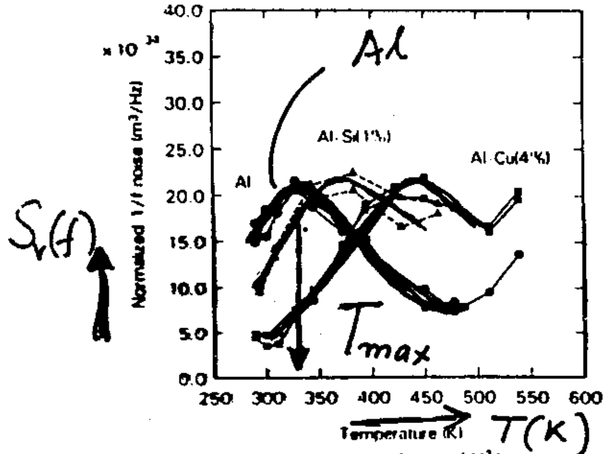


FIG. 1. Normalized 1/f noise $(S_V\Omega/V^2)$ vs temperature for six samples of three different compositions. The samples were $0.1\times4.5\times450$ μm^3 in dimension, unannealed, unpassivated, and measured with a current density of 2×10^6 A/cm^2 at a frequency of 10 Hz.

Al ——
Al (Si 1%) ——
Al (Cu 4%) ——

$\boxed{T_{max} \text{ fn. of } f}$

$$E_a\Big|_{noise} \approx -k_B T_{max} \ln(2\pi f \tau_0)$$

$$\tau_0 \approx 10^{-13} \text{ sec.} \quad f = 10 \text{ Hz}$$

For Al, $\boxed{E_a\Big|_{noise} \approx 0.7 eV}$

* Close to what has been seen by other methods for gb diffusi

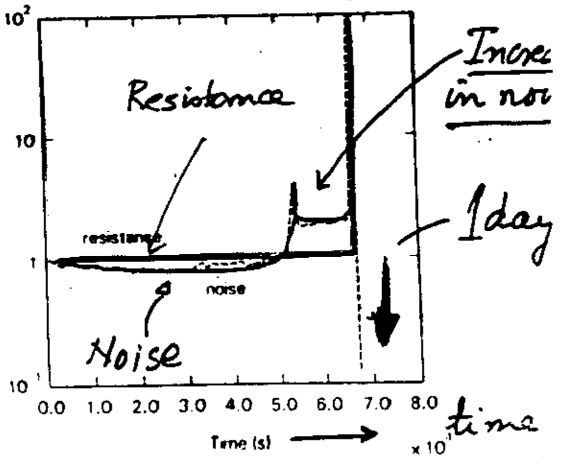


FIG. 3. 1/f noise and resistance vs time for an Al-Cu(4%) sample of Fig. 1. The noise magnitude, S_V/V^2, at 10 Hz and the resistance were normalized to the initial values at $t=0$. The oven temperature was 500 K, and the nominal current density was 2×10^6 A/cm^2.

* Change in noise power and its large enhancement before film failure

$T = 500 K$, $J \approx 2\times10^6$ A/cm^2

$I \approx 9$ mA.

Film fails ~ 1 day

Why does a metallic interconnect fail ?

Main reasons :

1. Electromigration (Mass transport in a current carrying conductor due to the passage of the current).

Very Important

This happens irrespective of existence of strain in the film

The "silent movement" of atoms as it Carries Current.

*2. Thermal hillock formation (Inelastic deformation of the film to relieve the compressive stress when heated)

*3. Stress voiding (Formation of slits and wedge type voids at the grain boundaries)

*4. Grain collapse (Inelastic deformation under tensile stress . Occurs in the scale of individual grains and cause the grains to be depressed relative to the surrounding grains)

* 2,3,4 all occur to relieve built in stress in the films and is a result of stress cycling at elevated temperatures.

Basic facts about electromigration (EM) :

Review ① H. B. Huntington - "Diffusion in Solids - Recent Developments" (Ed. Nowick & Berry, AP 1975)
② R. S. Sorbello, MRS Symp Proc. 225, 3 (1991)

First observation goes back to 1860 (Molten alloys and Na-Hg amalgam)

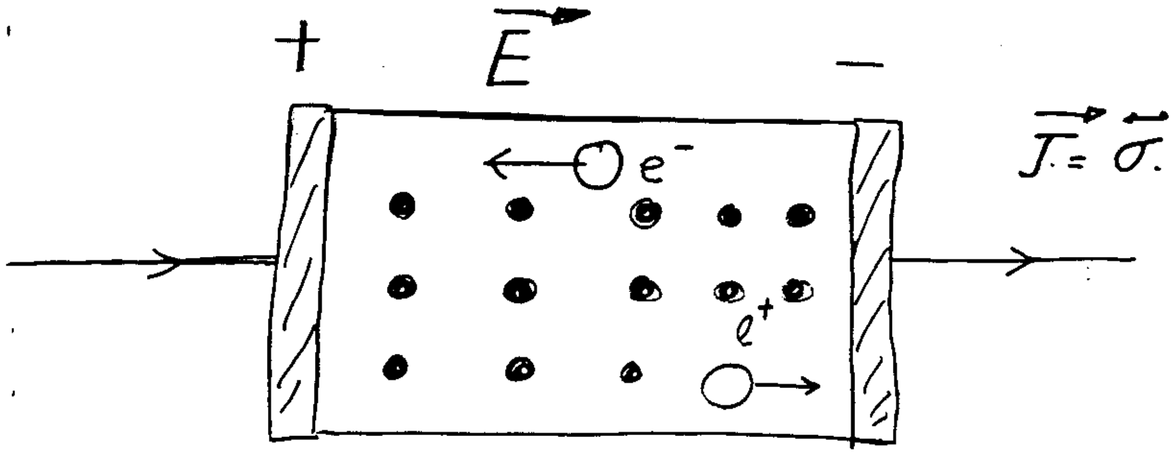
Renewed interest started in 1955-60

A very serious issue with IC failure and reliability from mid 1960. (Technology Drive)

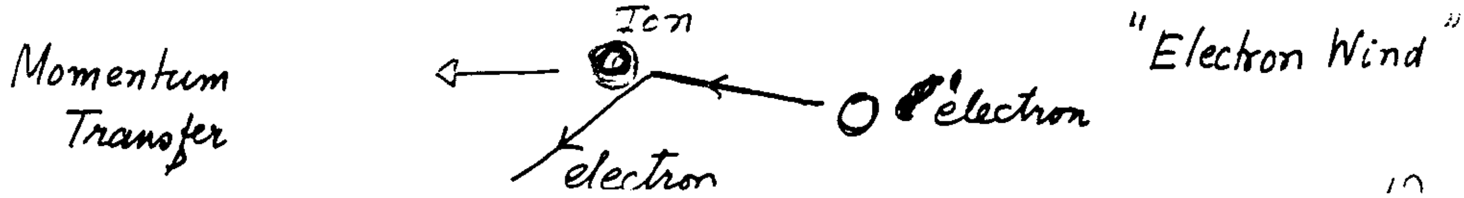
With increasing power of the microscopy the experiments are increasingly becoming clear and definite

MRS Symp. Proceedings "Materials and reliability issues in Microelectronics"

Basic issue: Momentum exchange of the moving charge carrier with ions of the lattice leading to mass motion.



$\vec{J} = \vec{\sigma} . \vec{E}$



Basic numbers

1. Magnitude and direction:

Force on the ion in a field $\vec{E}$ = $\vec{F} = |e| * Z^* * \vec{E}$

Z^* = effective charge . measure of the strength of EM . Typical $Z^* \approx 0.1 - 100$

$$\boxed{Z^* = Z_{el} + Z_{wd}}$$

Z_{el} = Formal valency . Z_{wd} = pressure due to electron (or hole) wind. Z_{wd} mostly dominates

If there are two types of carriers (h and e) :

$$Z_{wd} = -n_e \lambda_e \sigma_e + n_h \lambda_h \sigma_h$$

n = charge density, λ = mean free path,

σ = scattering cross section

(Ions move in the direction of the carriers)

If, $|Z_{el}| > |Z_{wd}|$ (which is usually the case) due to electron (or hole) wind the ions move in the direction of electron (or hole)

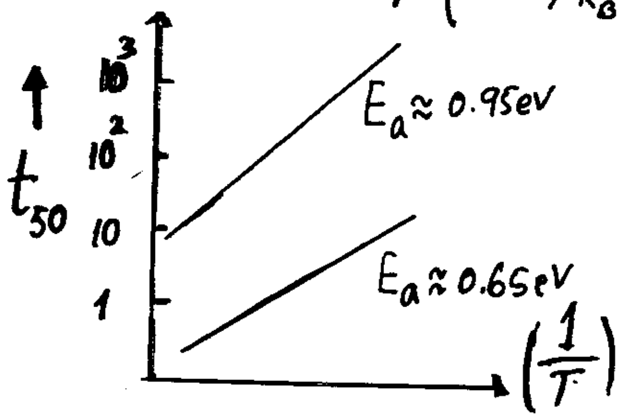
e.g., if electrons dominate then ions move towards anode !!

2. The likely spot of electromigration and its activated nature :

(<u>A statistical definition</u> : generally EM tests are carried out at higher temperatures R.T < T < Melting point. Mean time to failure (t_{50}) is defined as the time when 50% of the interconnects fail in a given test condition.)

Thermally activated nature of EM

The activation energy (E_a) ≈ the activation energy of vacancy diffusion at the <u>grain boundary</u> <u>(GB)</u> $t_{50} \propto J^{-2} T^{2} \, Exp\left(E_a / k_B T\right)$



Observation supported by electron microscopy

Electromigration occurs due to diffusion along grain boundaries because the E_a for diffusion is the least at the grain boundaries (Important role of gb. in polycrystalline films)

3. How to prevent EM at the grain boundaries ?

STOP (or reduce) migration of the vacancies at the grain boundaries.

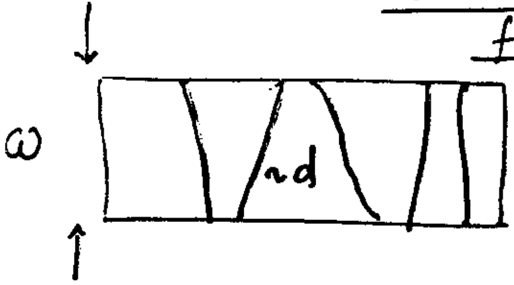
1. Small amount of another element which segregates or forms another intermetallic at the grain boundaries (e.g., 0.5- 1 at.% Cu in Al)

2. Reduce the width of interconnects : ω = width of film

(i) $\boxed{\omega \sim d}$

Bamboo Grains

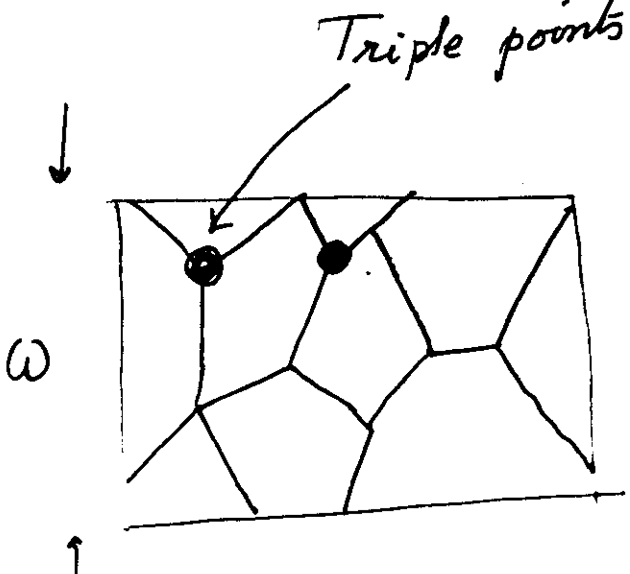
Higher activation Energy



(ii) $\boxed{\omega > d}$

Larger # of boundaries with triple points! Reduced E_a (enhanced diffusion) at triple points

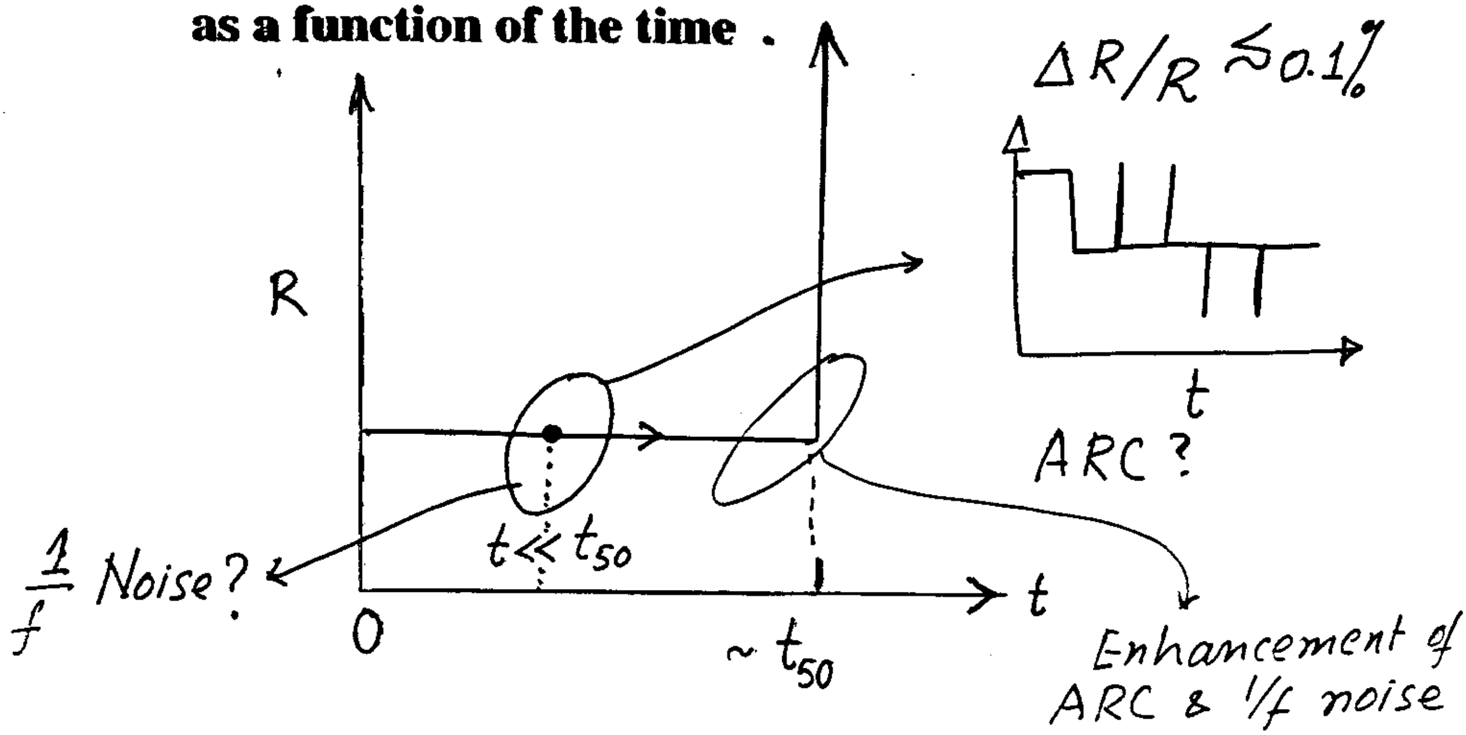
e.g., Al-1% Si



$\omega \approx 0.6\,\mu m \rightarrow E_a \approx 0.9\,eV$

$\omega \approx 5.0\,\mu m \rightarrow E_a \approx 0.6\,eV$

The behaviour of resistance of the interconnect as a function of the time .



Can we predict from any technique at $t \approx 0$ what will happen for $t \approx t_{50}$?

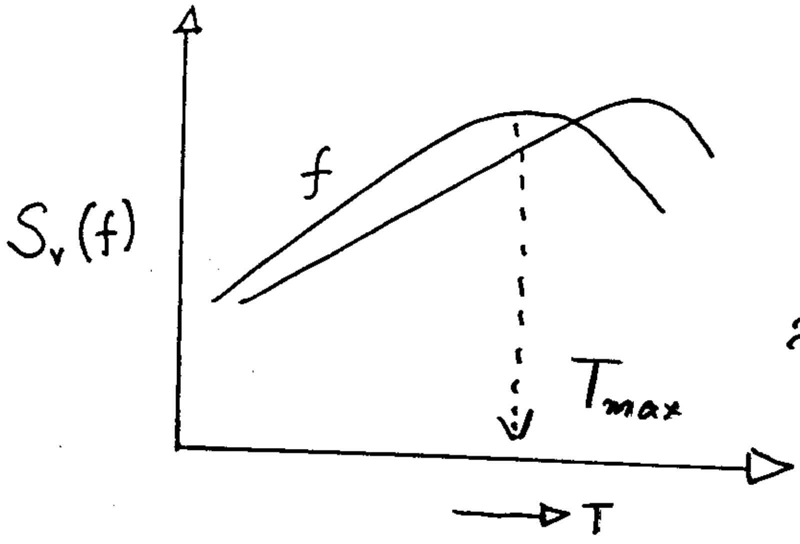
<u>Two likely (electrical) candidates</u> : noise and abrupt resistance changes (ARC) have the potential <u>for the prediction</u> without actually accelerating the failure at higher T or stressing current.*

* Failure tests are done at higher Currents $J \sim 10^6\ A/cm^2$ and elevated temperature ($T \approx 500K$) to <u>accelarate</u> failure.

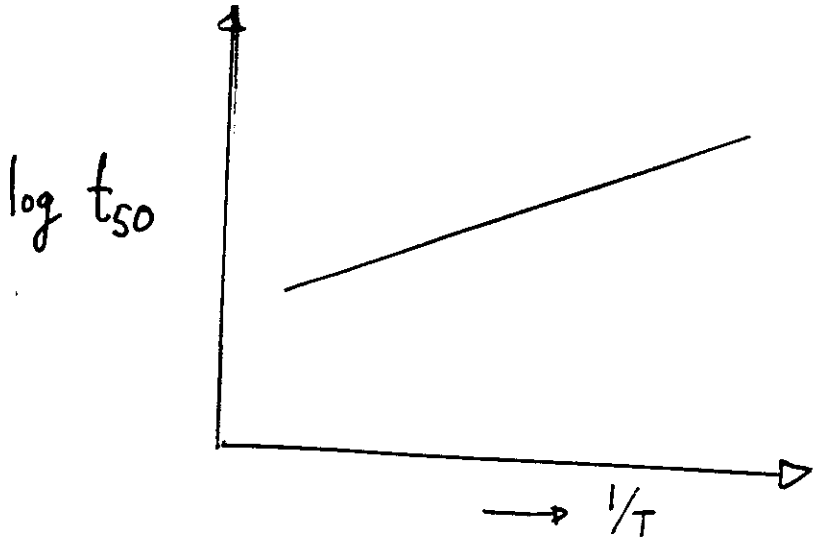
Important experiments

(The close connection between the ionic motions involved in the noise and the electromigration.)

(a) Activation energy associated with the peak in the temperature dependence of the noise power ≈ E_a, Activation energy associated with the vacancy diffusion in GB as in EM.



$$E_a|_{noise} \approx -k_B T_{max} \ln(2\pi f \tau_0)$$



$$t_{50} \propto \mathrm{Exp}\left(\frac{E_a|_{EM}}{k_B T}\right)$$

$$* \quad \boxed{\begin{aligned} & E_a|_{noise} \\ & \approx E_a|_{EM} \\ & \approx E_a|_{gb\ diffusion} \end{aligned}}$$

(b)

The dependence of the noise on the line width of the interconnect .

The normalised <u>noise power is less</u> in thinner interconnects which also have the less failure due to EM

$$\frac{S_V(f) * \text{Volume}}{V_{DC}^2}$$

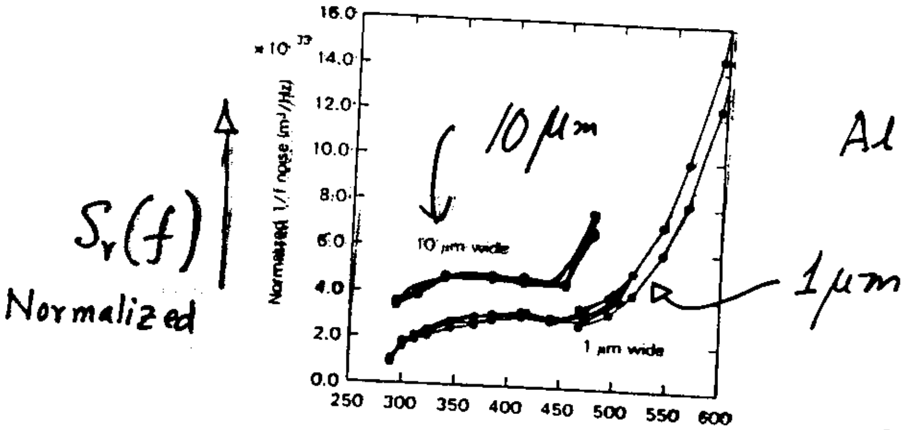


FIG. 2. Normalized 1/f noise ($S_V\Omega/V^2$) vs temperat for six samples of identical composition [0.15 μm of CrO-Cermet and 0.85 μm of Al-Cu(4%)] and length (μm), but differing widths. The samples were passivat annealed, and measured with a current density of 2× A/cm² at a frequency of 10

Al(4% Cu)

Koch et.al
PRL (1985)
↓
Kraayeveld et.al
MRS Symp 338, (1994)

<u>Noise decreases</u> as the <u>interconnect becomes Narrower</u>

→ Less diffusion at grain boundaries

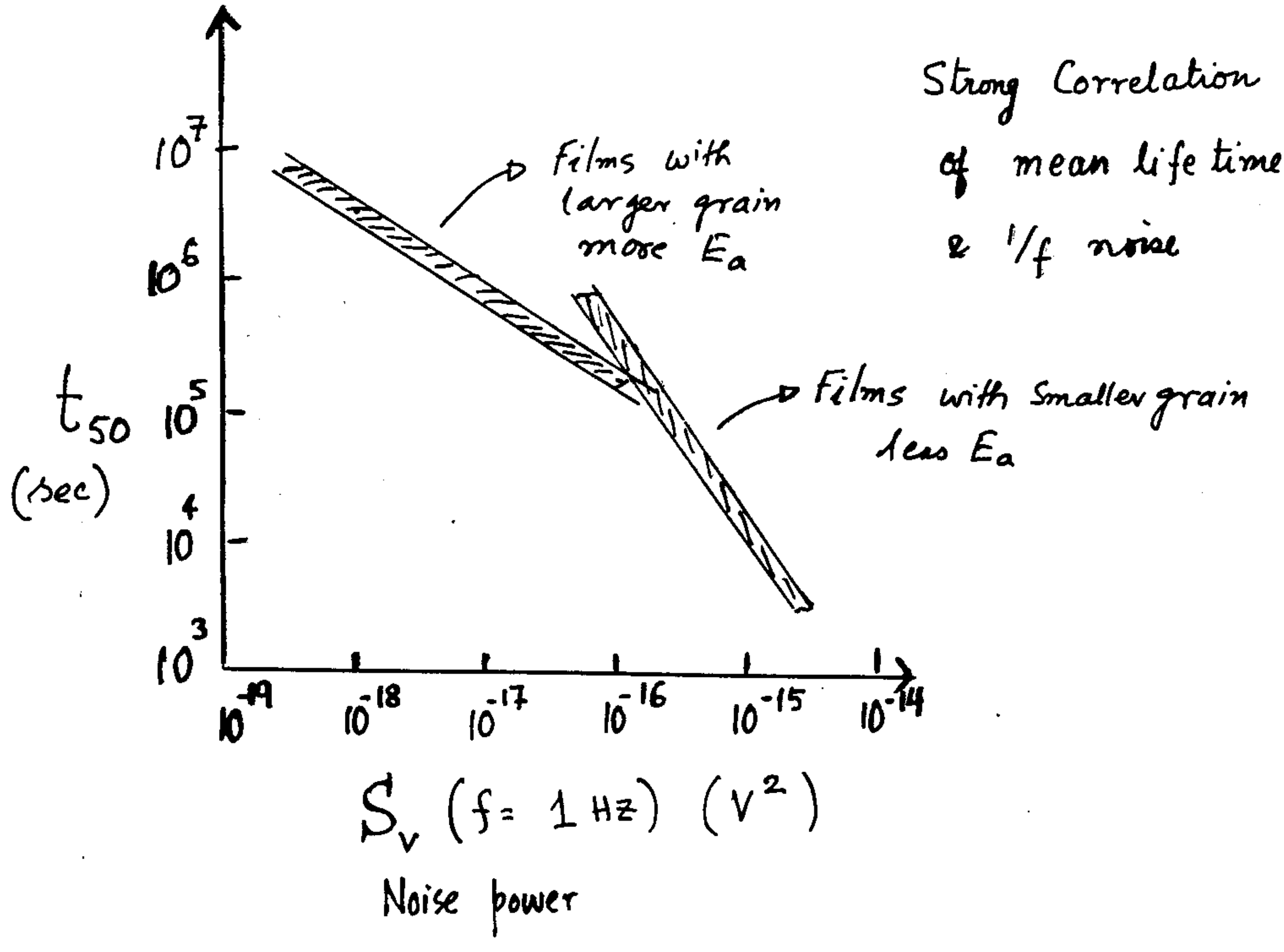
(Recall → less electromigration (longer t_{50}) in narrow lines)

(c) The dependence of the Mean time to failure (t_{50}) and the 1/f noise power intensity :

The <u>t_{50} is less</u> for films with <u>more noise intensity</u>

Cu interconnects

(why shift from Aluminium?)



Strong Correlation of mean life time & 1/f noise

Conclusion :

1. There is conclusive evidence that 1/f noise (and related conductivity noise) in a solid film are associated with the same atomic motion which give rise to electromigration in the grain boundaries leading to film failure.

2. The noise spectroscopy is a viable tool to study early signs of the film failure and characterise the quality of the film.

3. It has the potential for use as a predictive tool for assuring reliability of the metallic interconnects