Elementary Process of Electromigration at Metallic Nanojunctions in the Ballistic Regime

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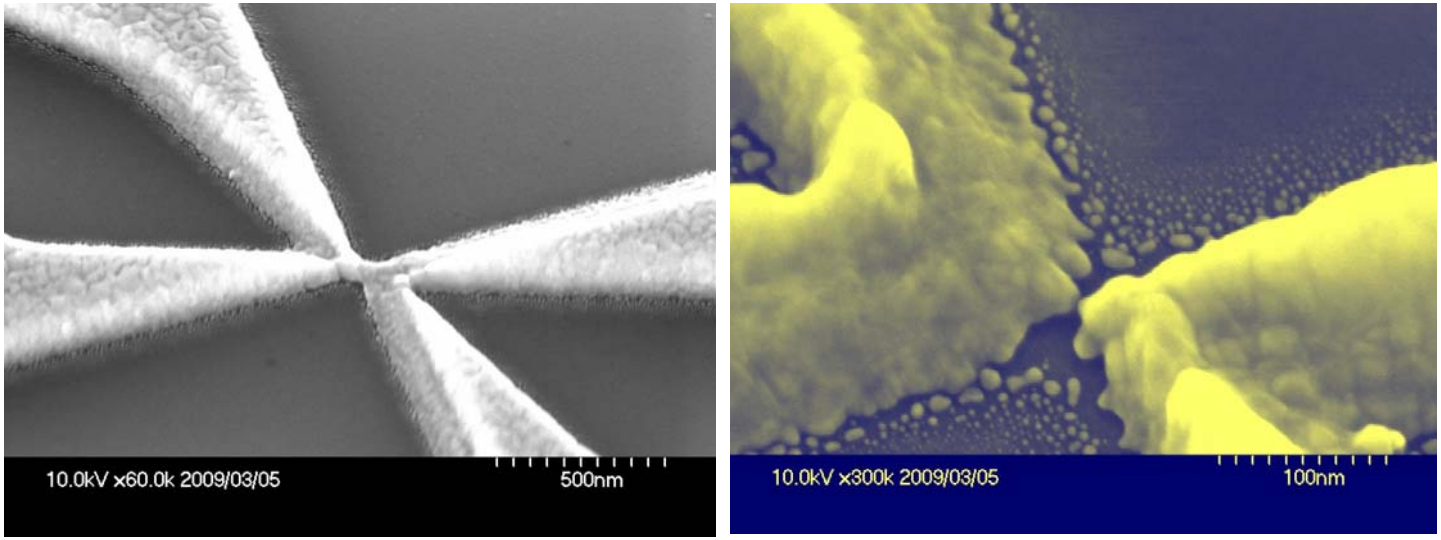
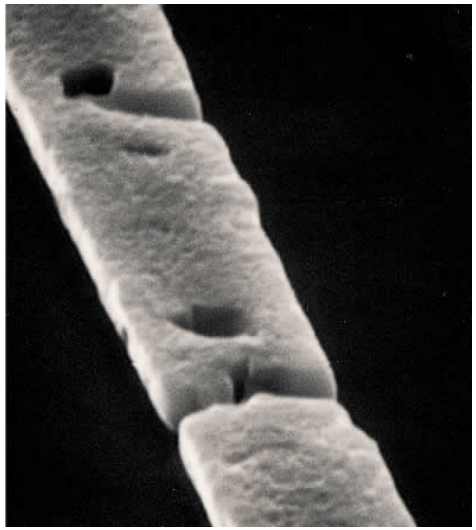


Outline

1. Introduction
   - Electromigration (EM)
   - Commonly believed mechanisms for EM
2. Feedback-controlled electrical break junction
   - Experimental
   - Critical voltage for atom removal events
     -- “EM spectroscopy”
3. Elementary process of EM
   - What is the crucial parameter in the ballistic regime?
   - Critical current density
4. Summary

Electromigration (EM)

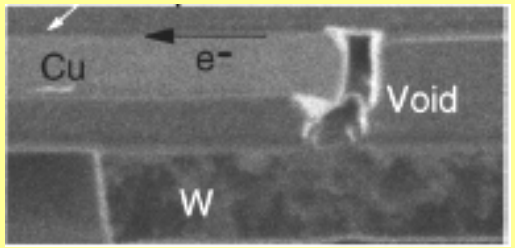
Blow-outs of fuses and filaments



http://www.semiconductor-sanyo.com/reliability/main.asp?id=M30A45&part=4

Failure of VLSI interconnects

IBM J. Res. Dev.
Cover of July 1995 issue



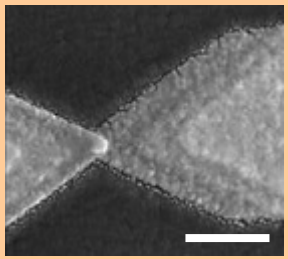
C. -K Hu et al., APL **81**, 1782 (2002).

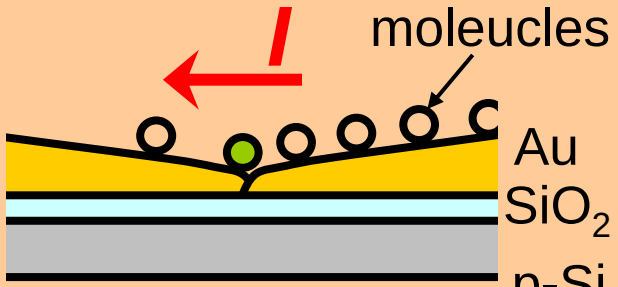
typical J_{max} = a few MA/cm²

- Limits the reliability of metal wires, filaments, and VLSI interconnects

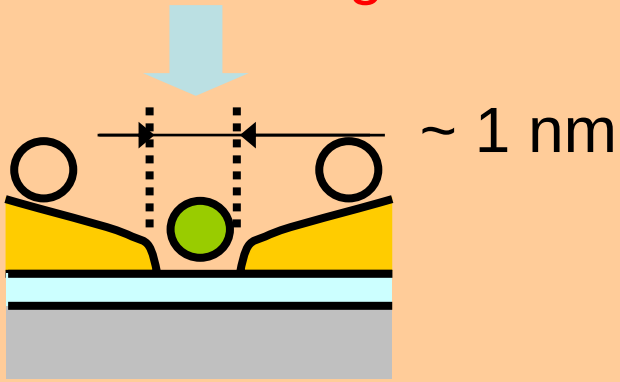
Formation of Atomic Scale Nanogap Electrodes

Fabricating Nanogap Electrodes





Electromigration

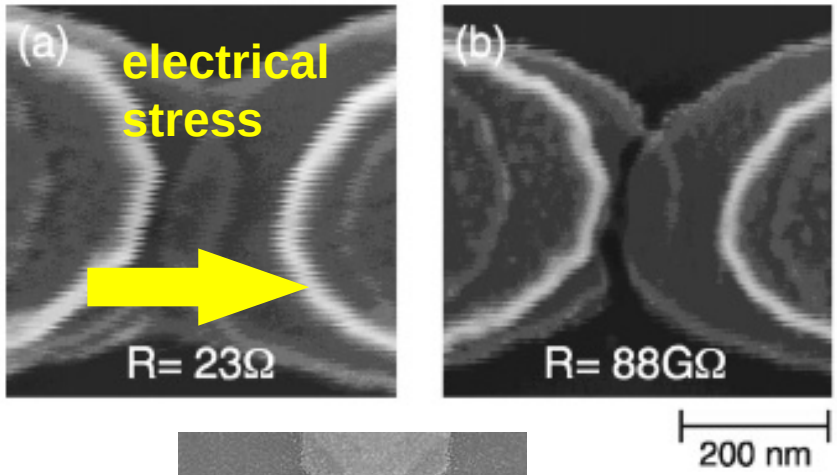


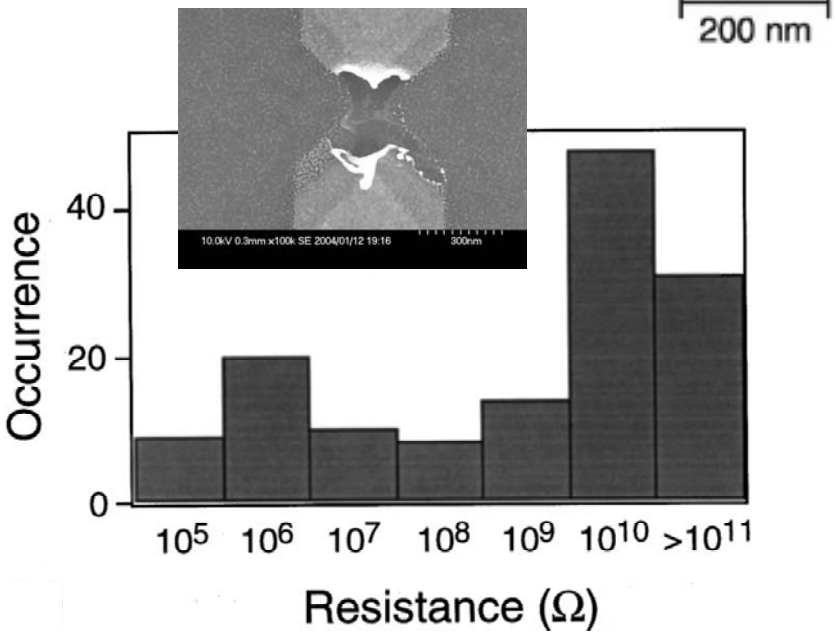
Molecular junction

H. K. Park, P. L. McEuen et al., Nature **407**, 57 (2000).

- Not always end up with “nanogaps”.
- Understanding of the physics of EM is very important !

“Nano-fuse”





H. K. Park et al., APL, **75**, 301 (1999).

Mechanism of Electromigration

① Joule heating

Rise in temperature

→ Enhances mobility of atoms

Critical Power Dissipation

$$P^* = IV = V^2/R$$

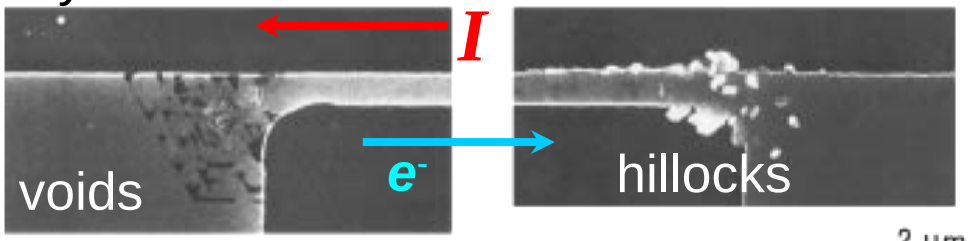
Mean Time to Failure (MTTF) of wires

$$\tau \propto \exp\left(E_a / k_B T\right) / j^n$$

② Electron wind force

Atoms are pushed

by momentum transfer from electrons



Critical Current Density

j^* ~ a few MA/cm^2

H. B. Huntington *et al*., J. Phys. Chem. Solids **20**, 76 (1961)

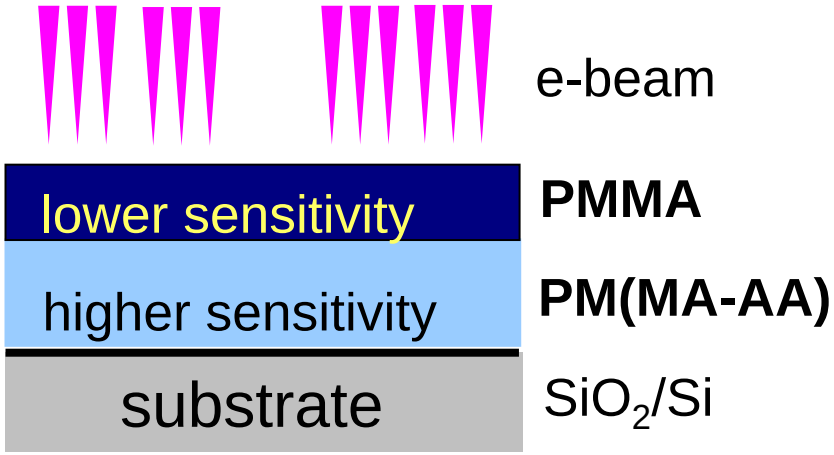
A. Scorzoni *et al*. Mat. Sci. Rep. **7**, 143 (1991) / C. Durkan *et al*. Ultramicroscopy **82**, 125 (2000)

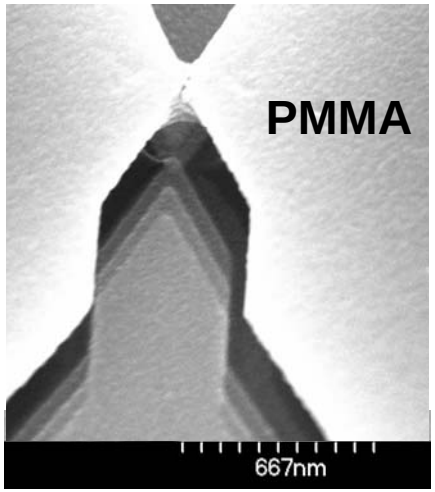
Purpose of this study

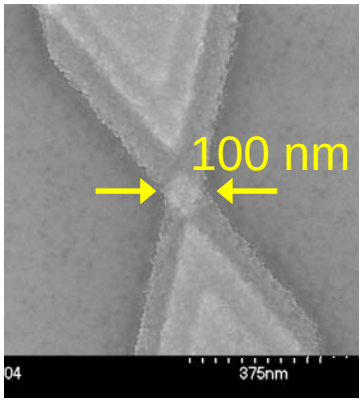
- To clarify the elementary process of EM in the atomic scale nanojunctions
- Novel analysis tool: “EM Spectroscopy”
- **Junction voltage** is the crucial parameter

Sample Preparation

- Double-layer resist EB lithography

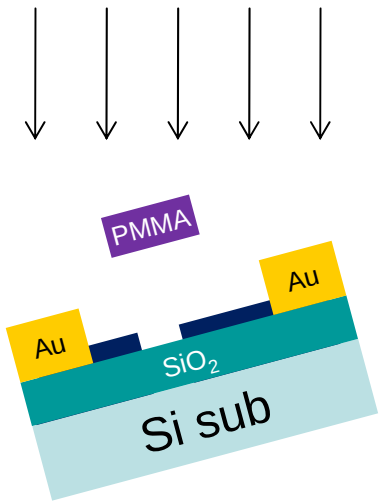




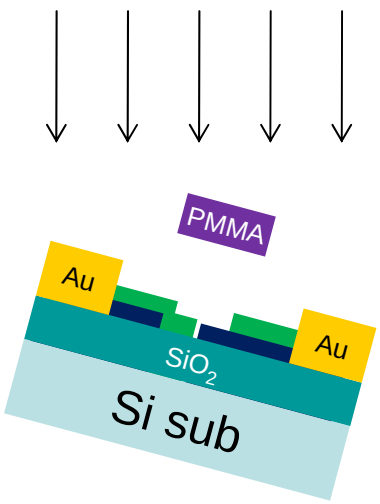


SEM image of the samples

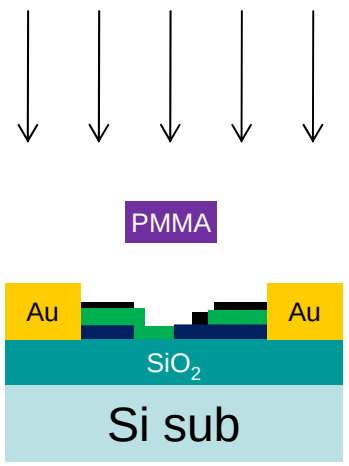
Shadow Evaporation



-11° tilt (1st layer)

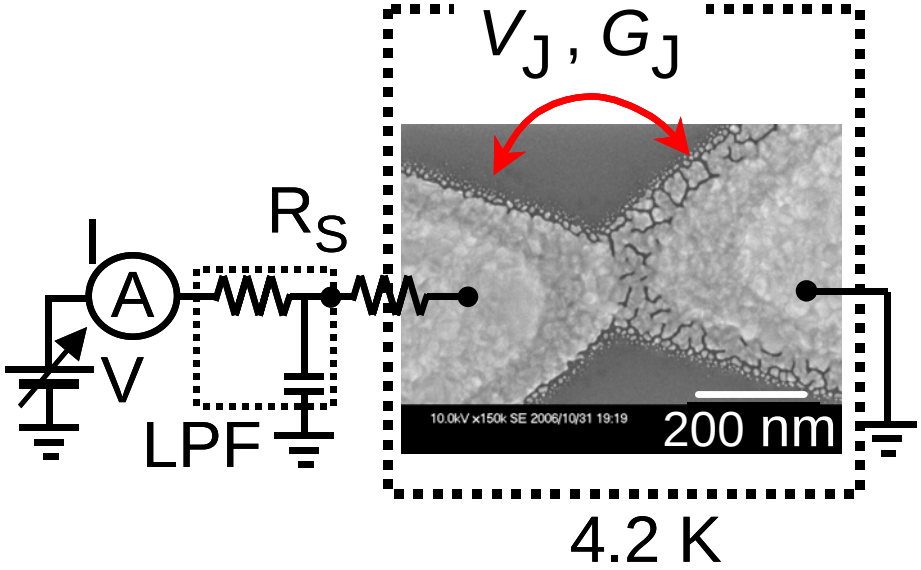


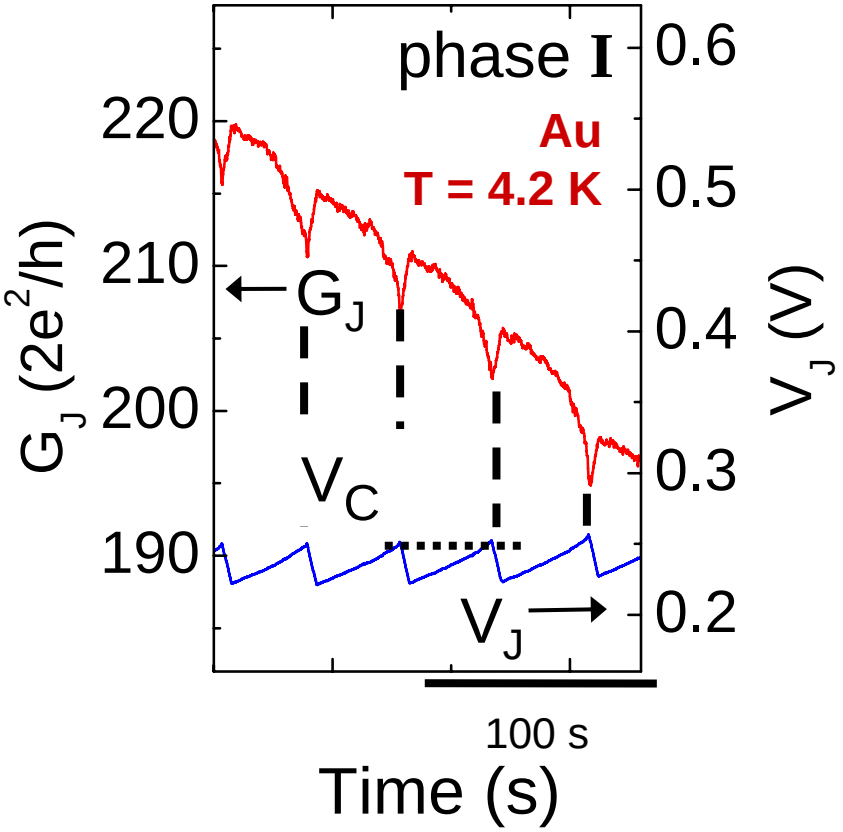
+11° tilt (2nd layer)



0° (3rd layer)

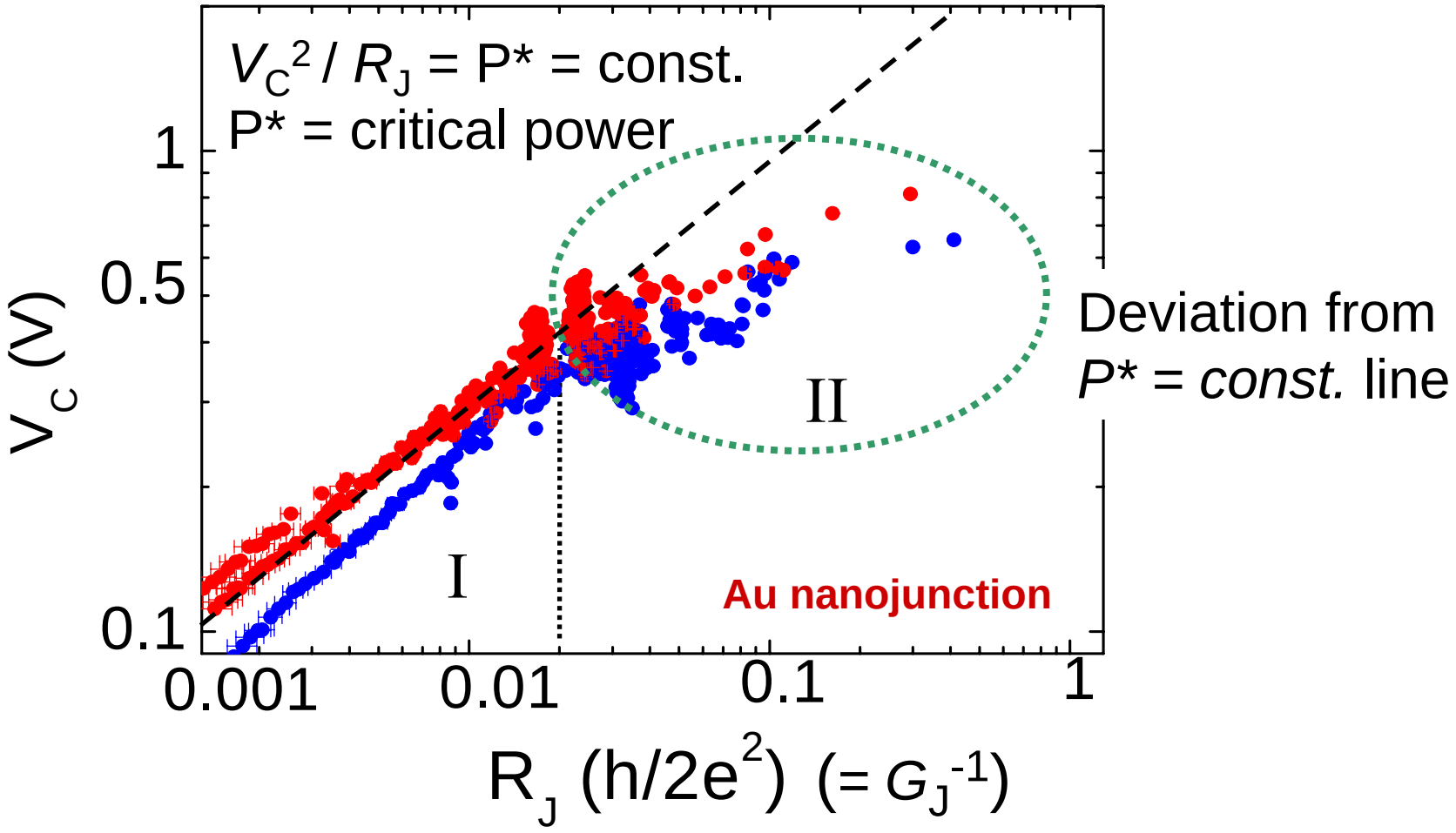
“Feedback-Controlled” Electrical Break Junction





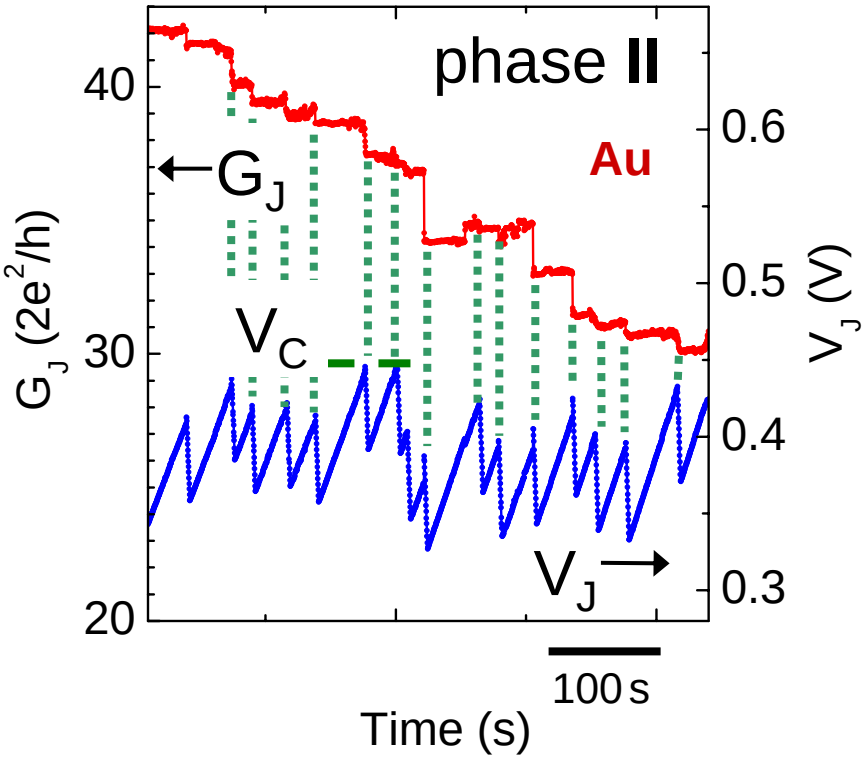
- Feedback control of EM D. R. Strachan *et al*. Appl. Phys. Lett. **86**, 043109 (2005)
  Sharp decreases in G_J (sign of EM) → reduce V
- Peak $V_J = V_C$ (critical voltage)

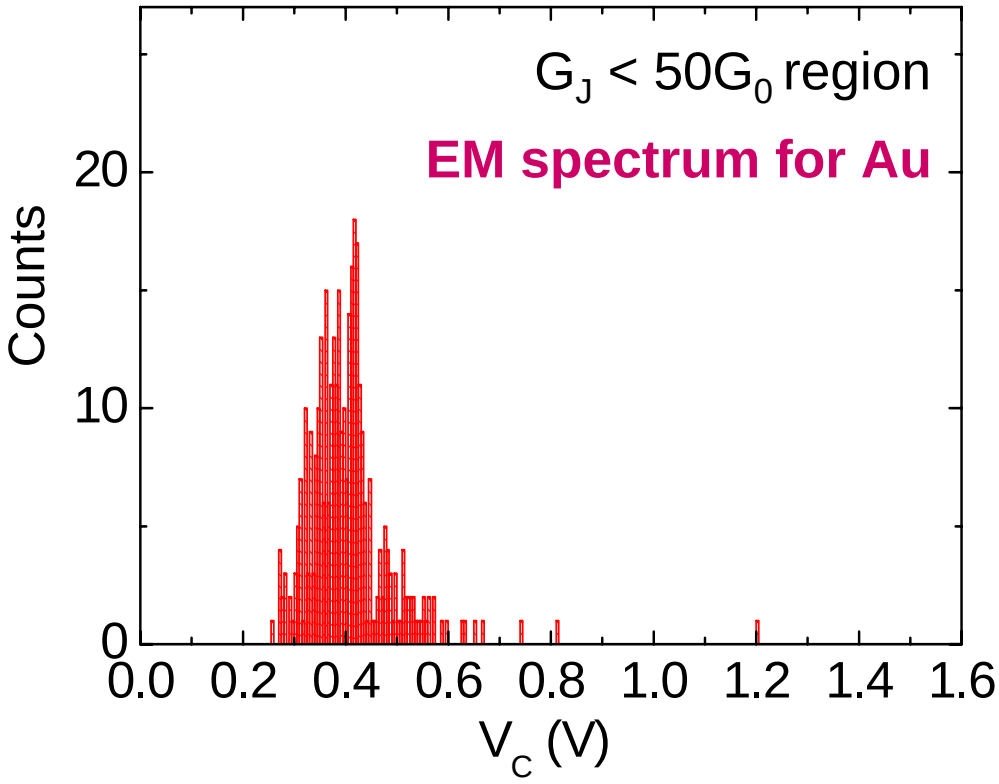
Semi-classical and Ballistic Regimes in EM



- Joule heating dominant for $G_J > 50\ G_0$ (Phase I)
- Deviation from the *P** = const. line for $G_J < 50\ G_0$ (Phase II)

Atomic-scale EM in Phase II ($G_J < 50G_0$)

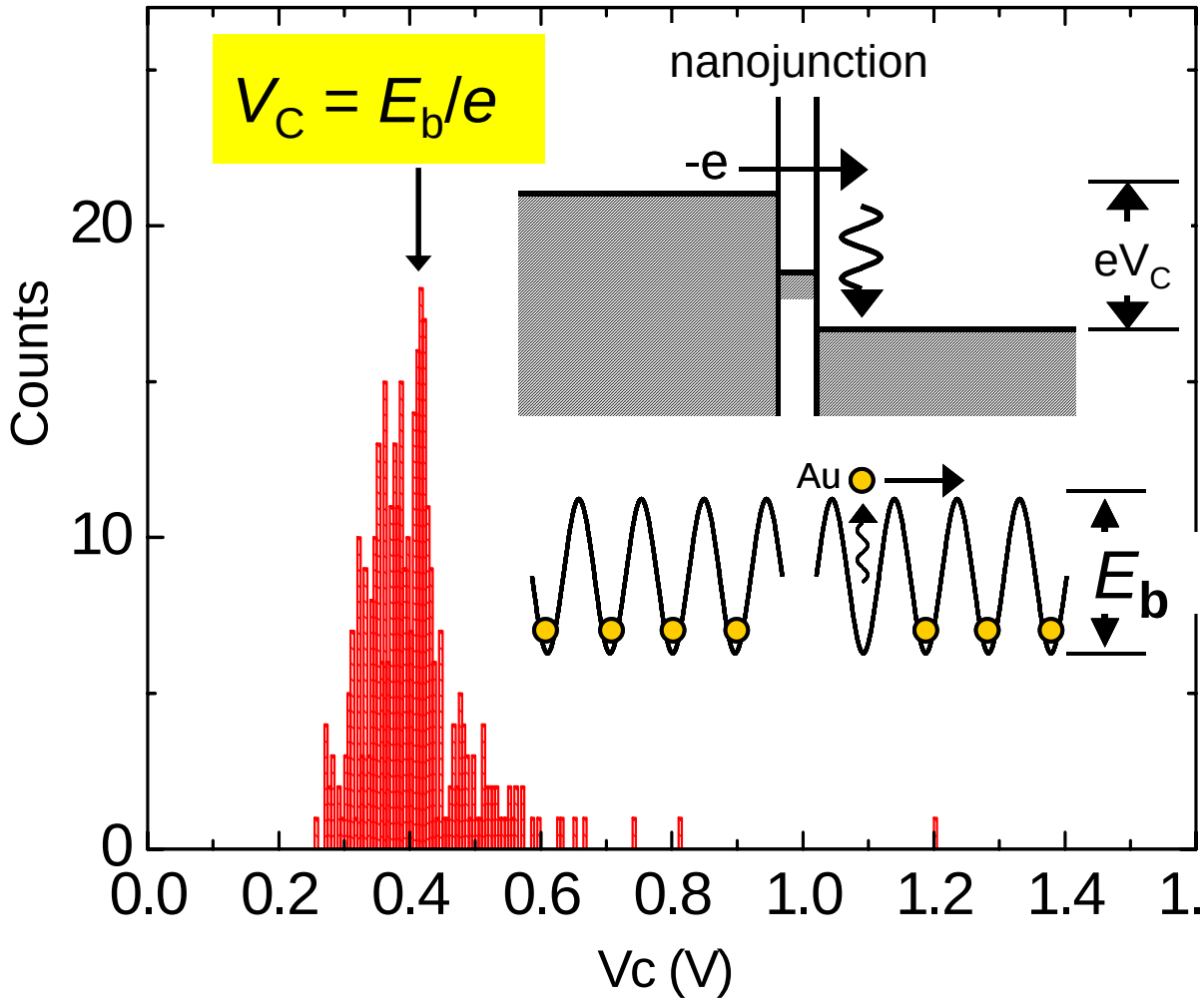




- G_J shows step-wise drops by ~ G_0
  - The junction is in the ballistic regime (QPC)
  - One-by-one removal of atoms from the junction
- Histogram of Vc

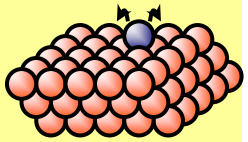
→ "EM Spectroscopy" (spectroscopy of atom removal events)

EM-Spectroscopy for Au Nanojunction
- Elementary Process of EM -



Surface diffusion potential : E_b

S. Günther *et al*.
Surf. Rev. Lett. (1997)



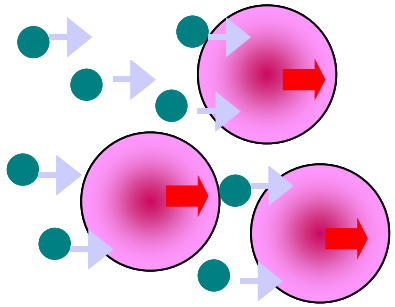
For gold

E_b = 0.4-0.44eV

STS measurement

Conventional picture

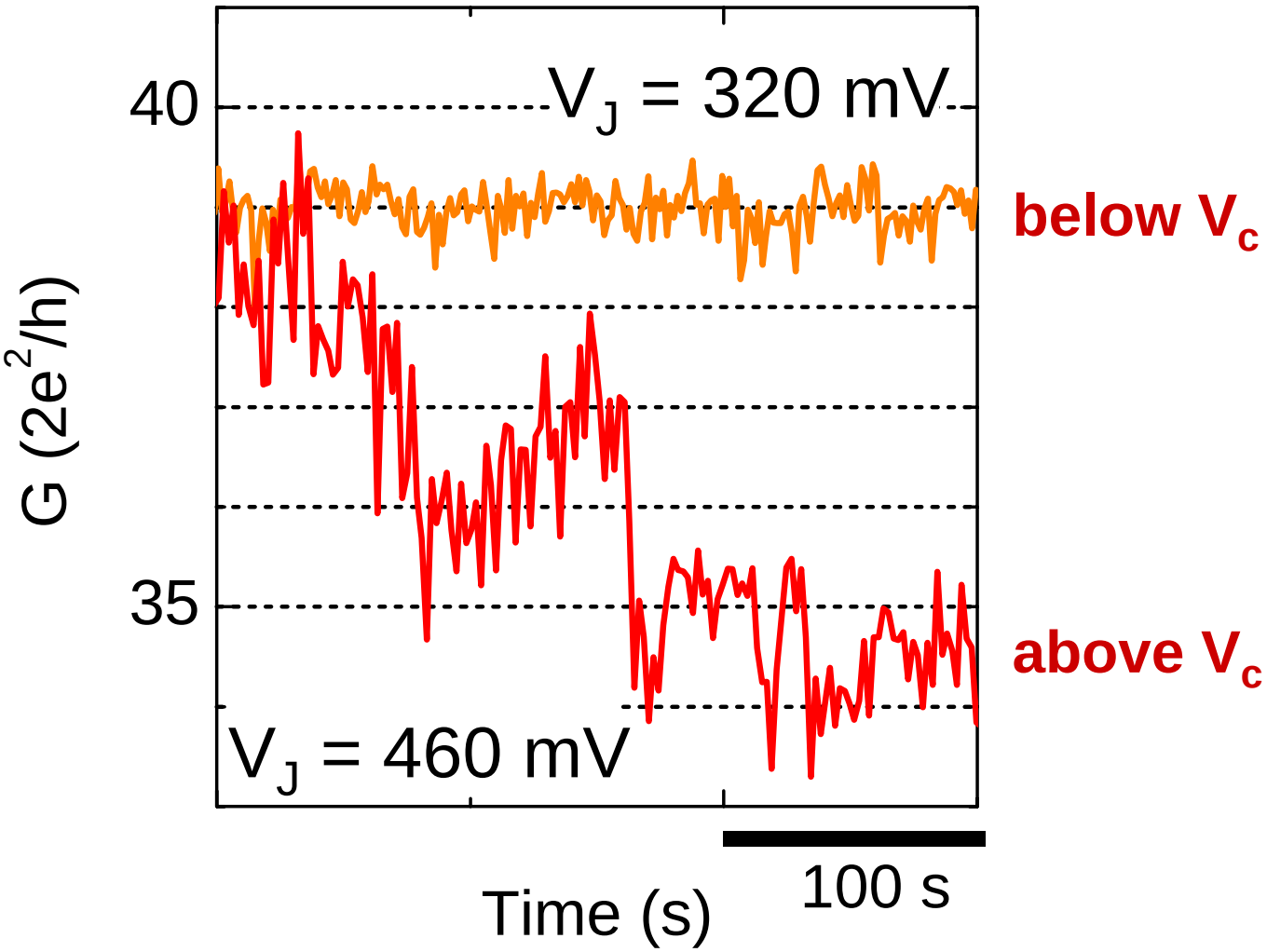
e-wind force



A. Umeno & K. Hirakawa,
APL **94**, 162103 (2009).

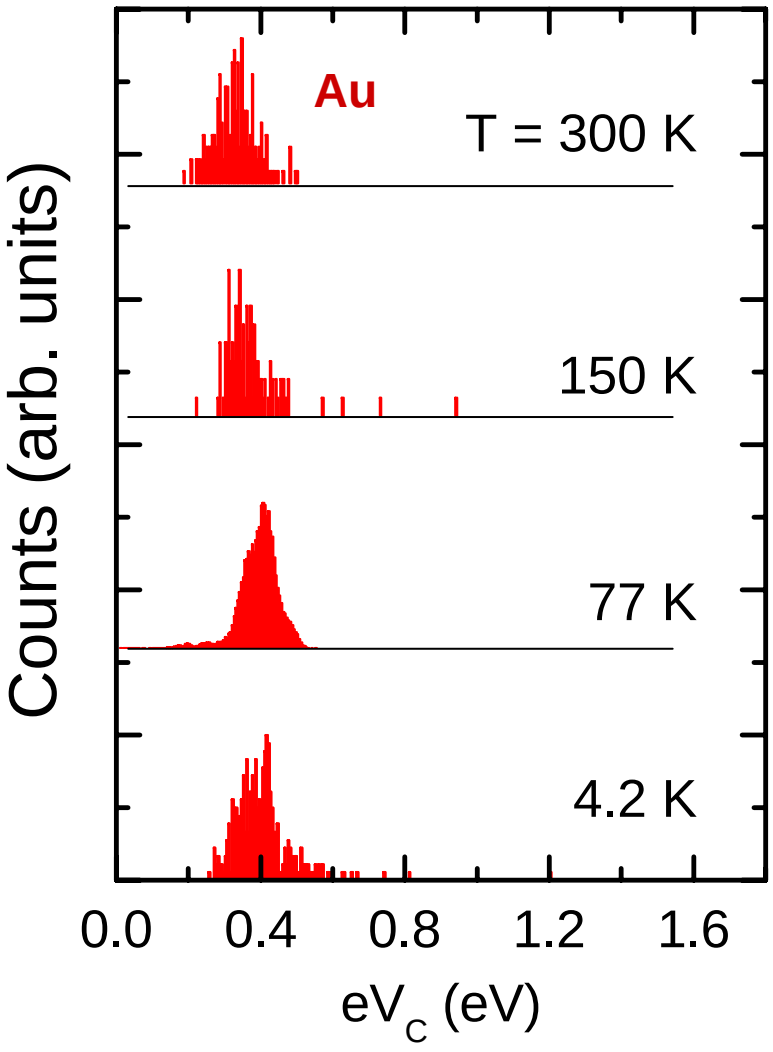
EM in the ballistic regime is induced by kinetic energy transfer from a single electron to a single atom.

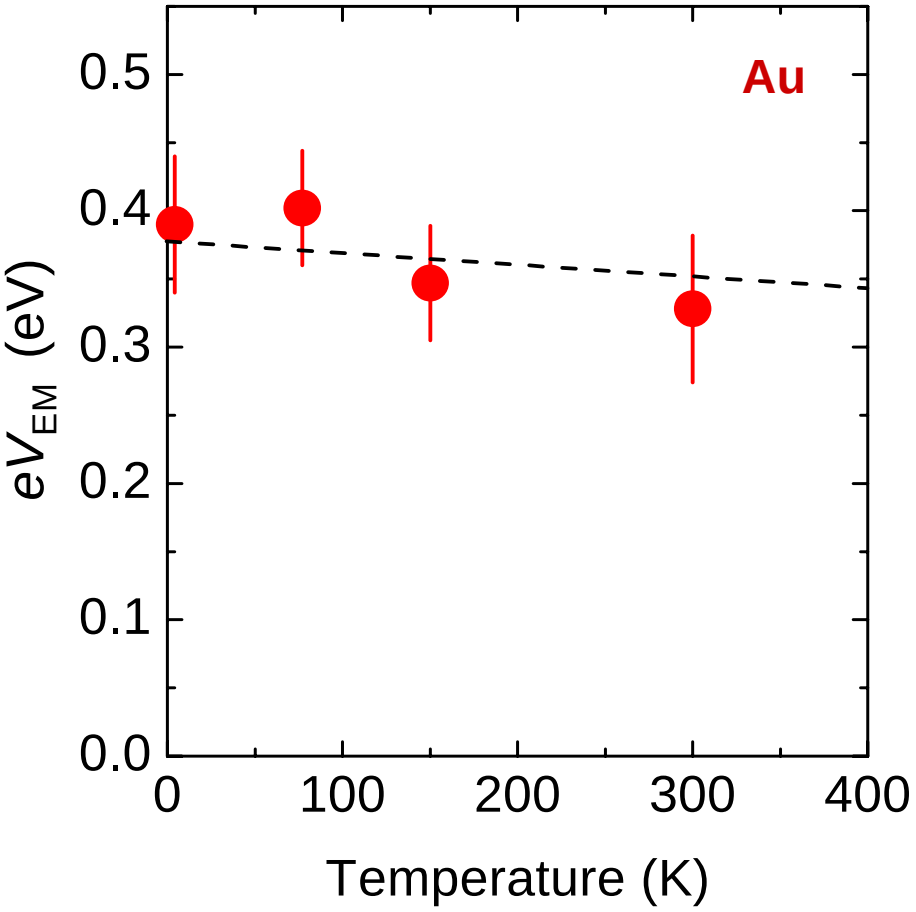
Critical Voltages for EM



EM does not develop unless V_J exceeds the critical voltage V_c (= E_b/e).

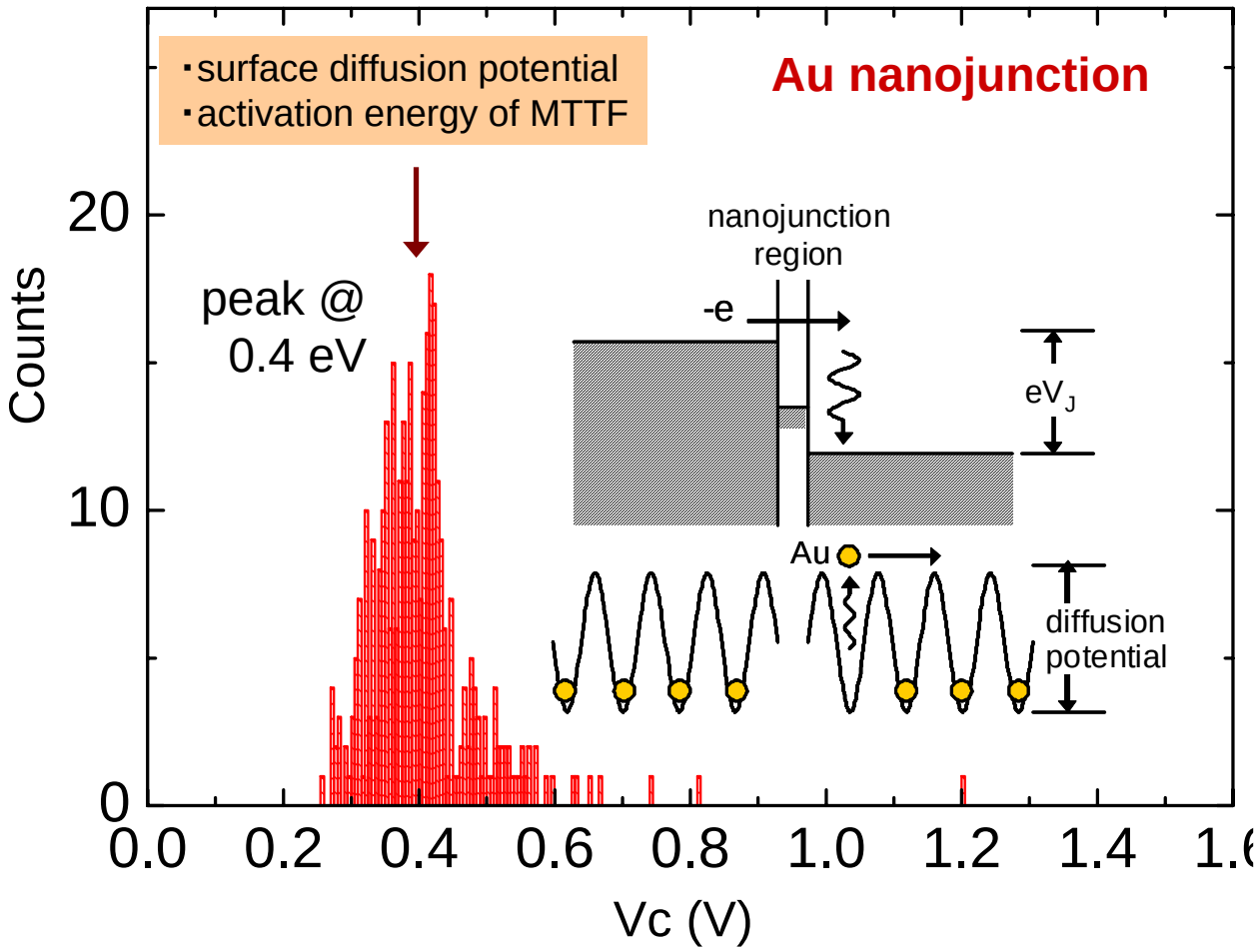
Critical Voltage in the Ballistic Regime

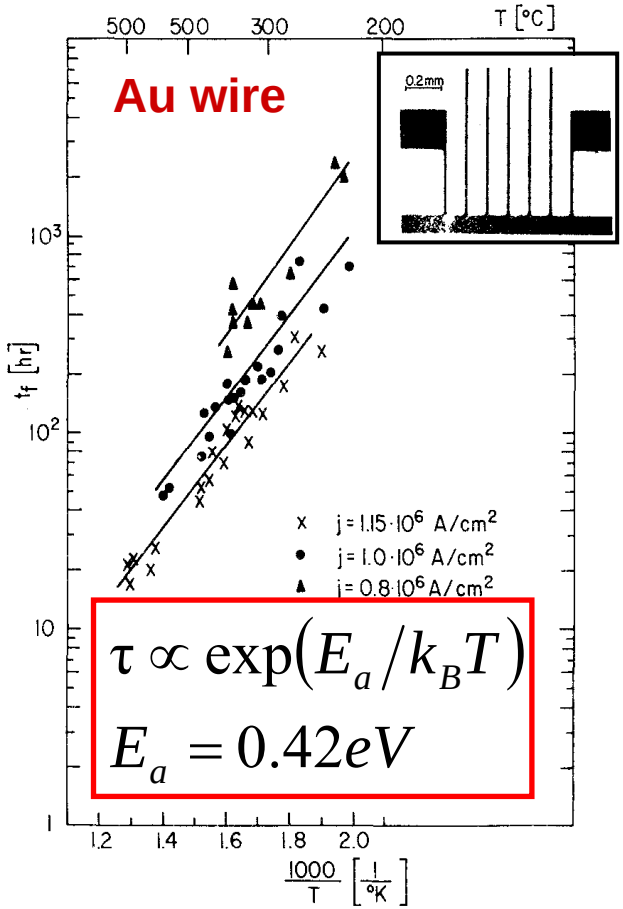




Almost no temperature dependence was observed in the EM spectrum.

Technological Implication of EM Spectra



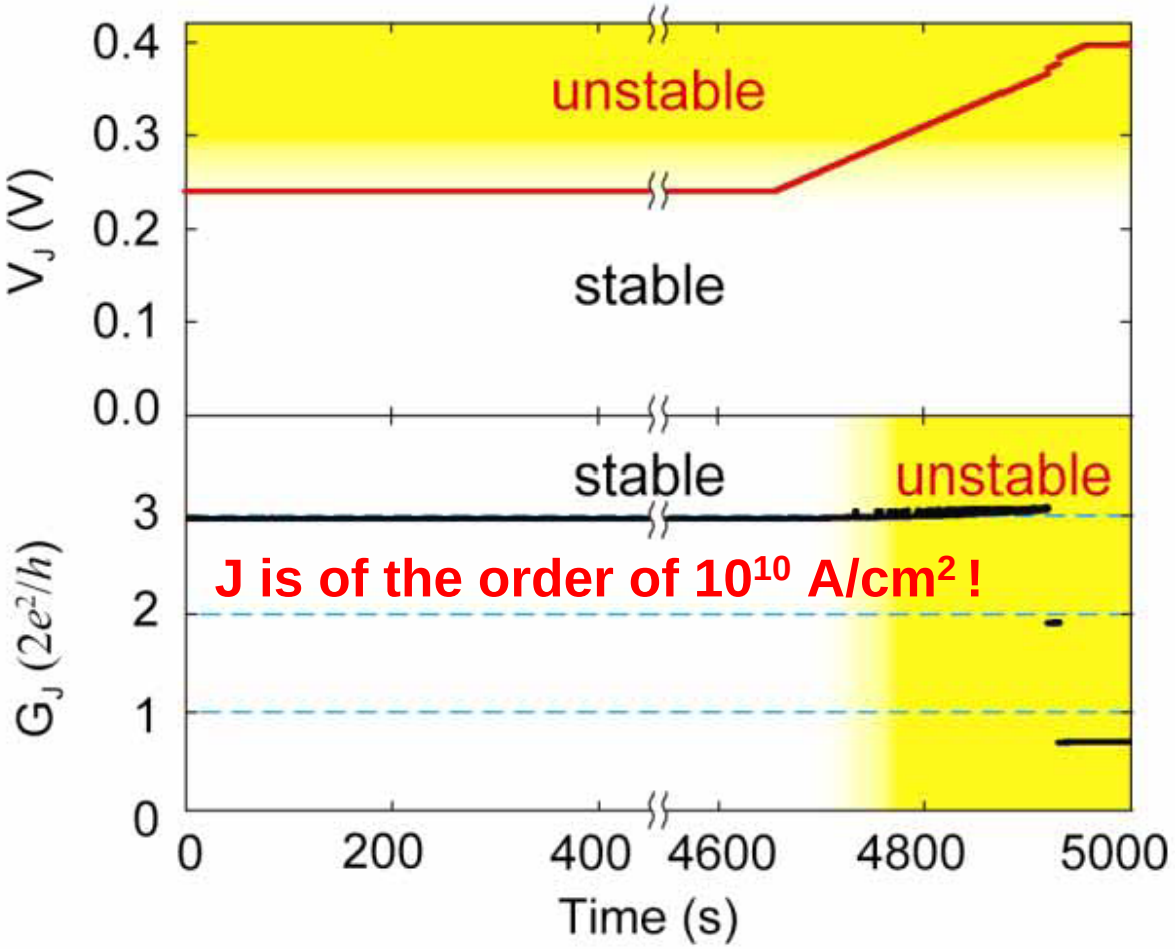


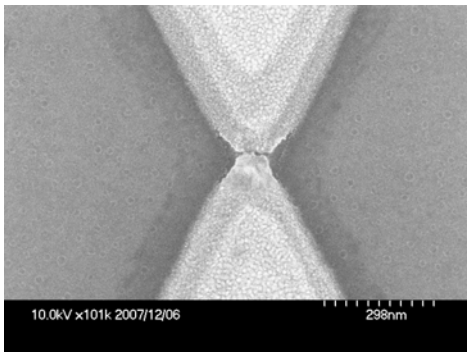
$$\tau \propto \exp\left(E_a / k_B T\right)$$

$$E_a = 0.42eV$$

- The EM spectrum has a peak at the activation energy for the mean time to failure (MTTF) of metallic wires.
- E_a can be determined from EM spectra.

Stability and Critical Current Density (V_C ~ 0.3 V for Ni)





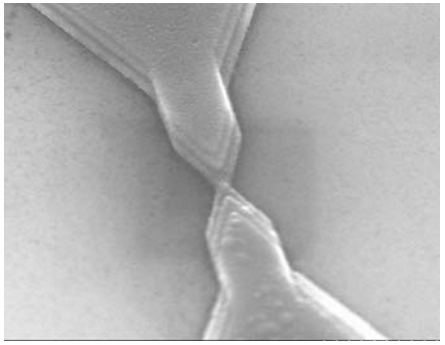
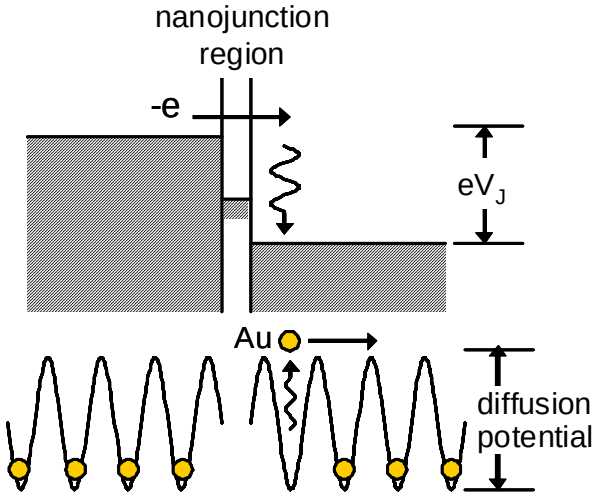
Ni nanogap electrode

K. Yoshida, A. Umeno, S. Sakata, and K. Hirakawa, submitted.

- When $V_J < V_C$, a 3-atom Ni junction is very stable.
- The current density is of the order of 10^{10} cm^2, which is 4 orders of magnitude larger than the critical current density known for EM.

Summary

We have investigated the elementary process of EM in the ballistic regime by introducing a novel spectroscopic approach (“EM spectroscopy”)

- EM is induced by kinetic energy transfer from a single electron to a single atom.
  - The crucial parameter is the junction voltage, not the current density !
  - $V_C \sim E_d/e$
  - Metal junctions are stable even when $j \sim 10^{10}$ A/cm^2, as long as $V_J < V_C$.

- Scientific/technological implications
  - Reliability of VLSI interconnections