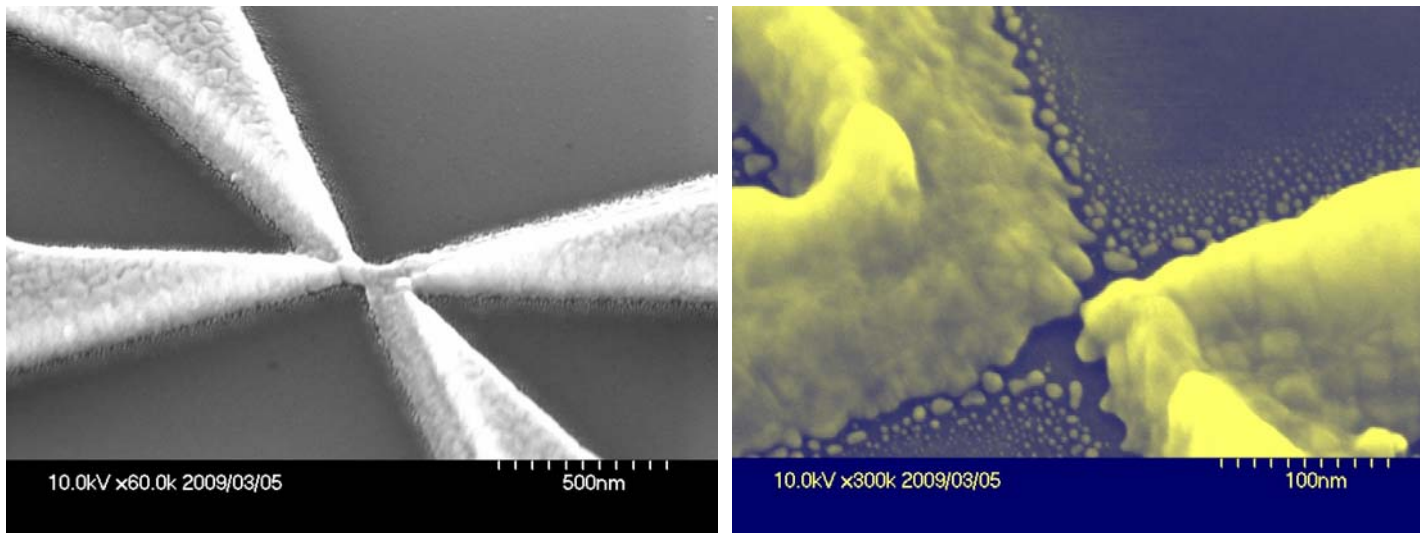


# Elementary Process of Electromigration at Metallic Nanojunctions in the Ballistic Regime

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collaborators: Akinori Umeno, Kenji Yoshida, and Shuichi Sakata



# Outline

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## 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

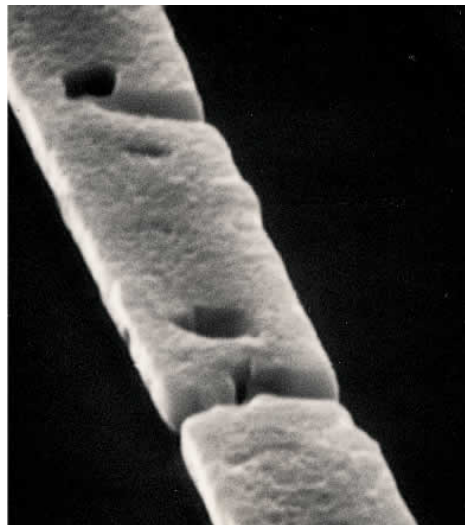
- What is the crucial parameter in the ballistic regime?
- Critical current density

## 4. Summary

# Electromigration (EM)

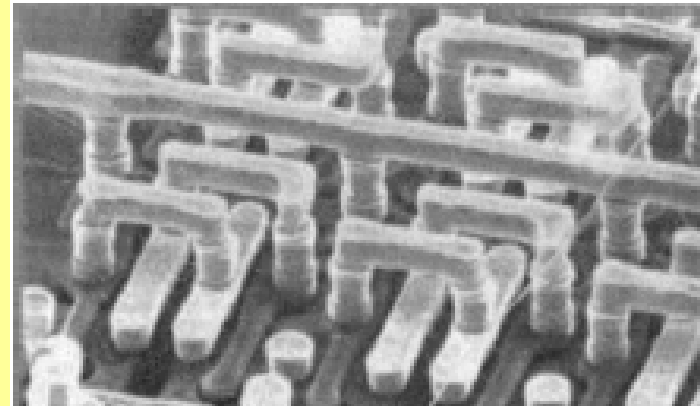


**Blow-outs of fuses and filaments**

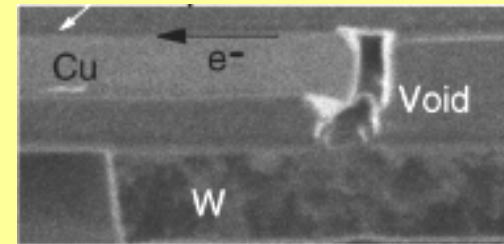


<http://www.semiconductor-sanyo.com/reliability/main.asp?id=M30A45&part=4>

## Failure of VLSI interconnects



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



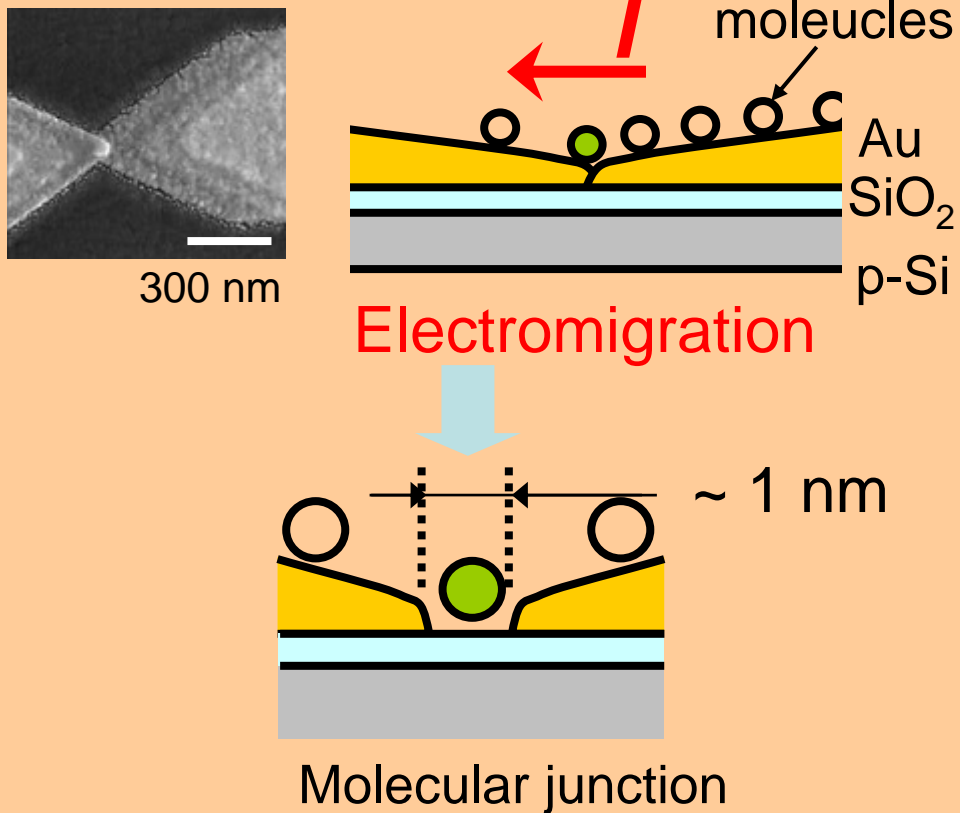
C. -K Hu et al., APL **81**, 1782 (2002).

**typical  $J_{\max}$  = a few MA/cm<sup>2</sup>**

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

# Formation of Atomic Scale Nanogap Electrodes

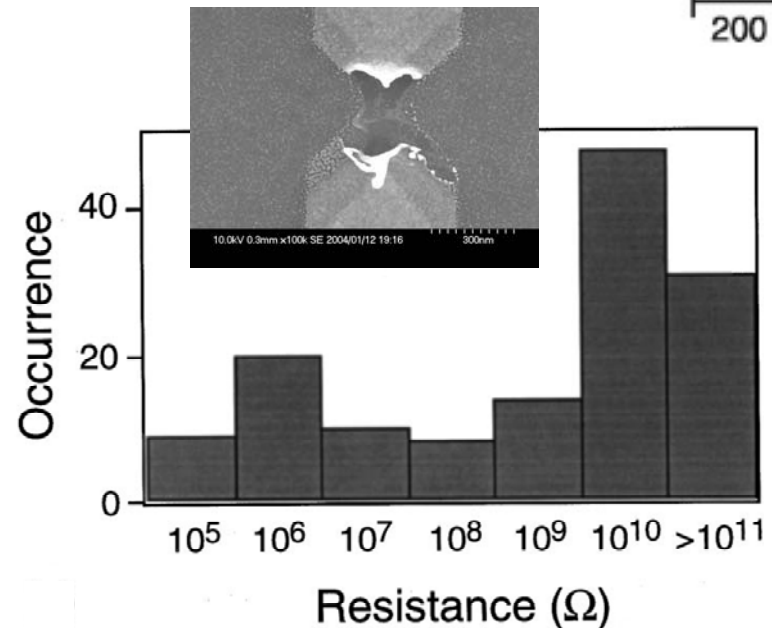
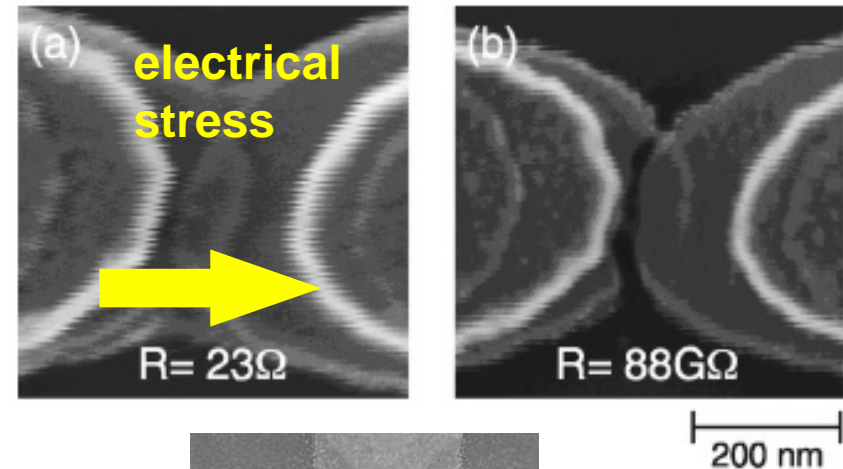
## Fabricating Nanogap Electrodes



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

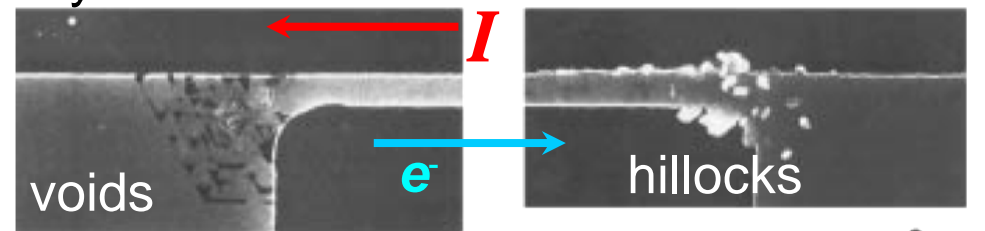
$$P^* = IV = V^2/R$$

Mean Time to Failure (MTTF) of wires

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

## ② Electron wind force

Atoms are pushed  
by momentum transfer from electrons



Critical Current Density

$$j^* \sim \text{a few MA/cm}^2$$

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

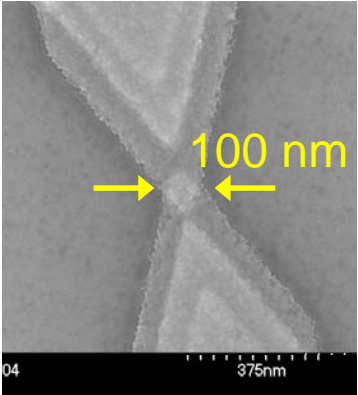
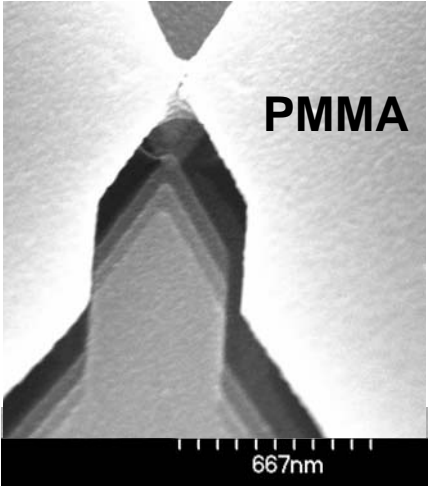
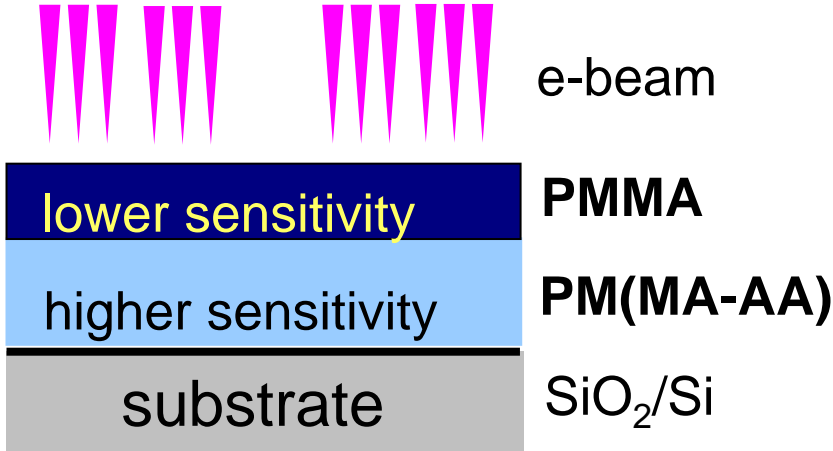
A. Scorzoni *et al.* Mat. Sci. Rep. **7**, 143 (1991) / C. Durkan *et al.* Ultramicroscopy **82**, 125 (2000)

## 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

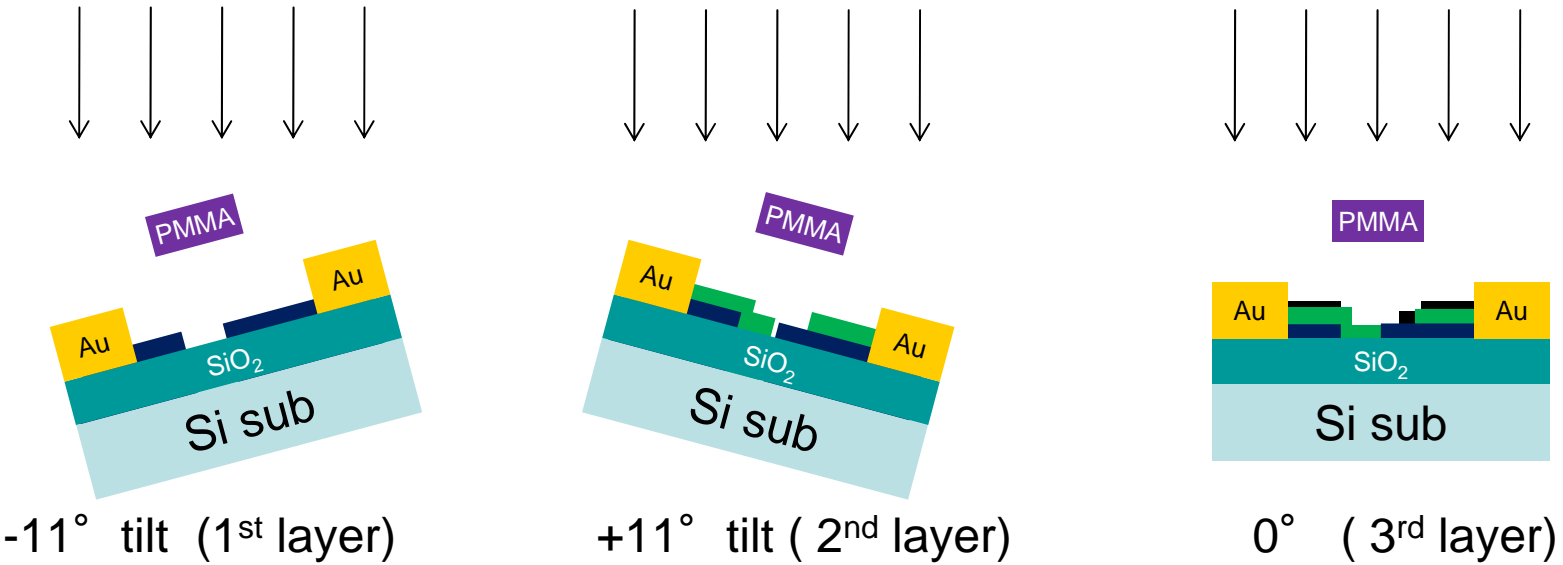
# Sample Preparation

## Double-layer resist EB lithography

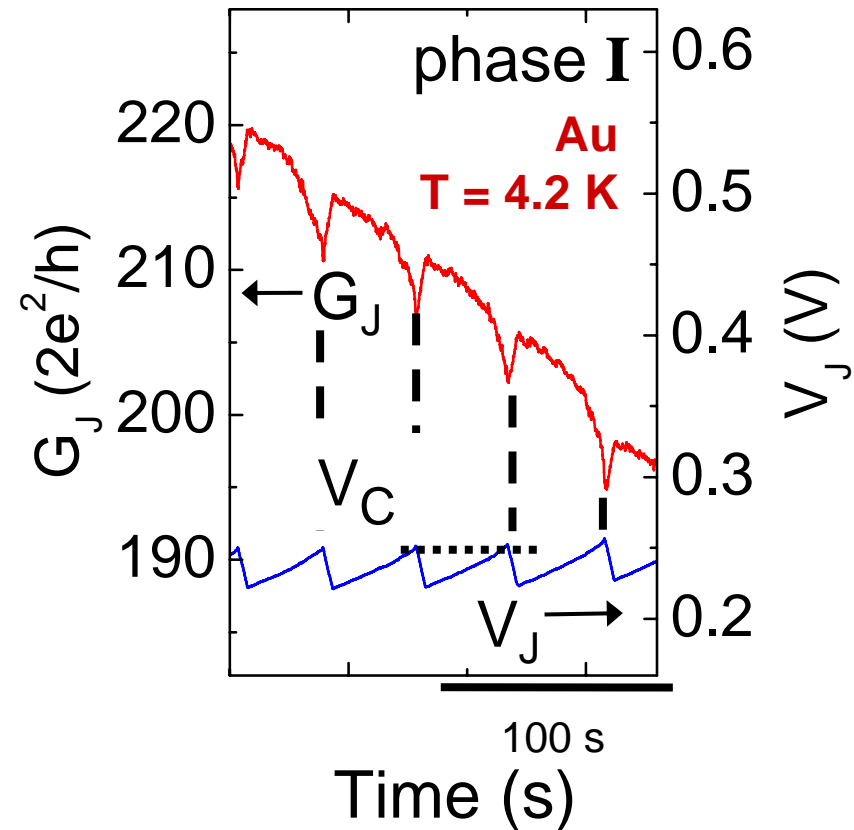
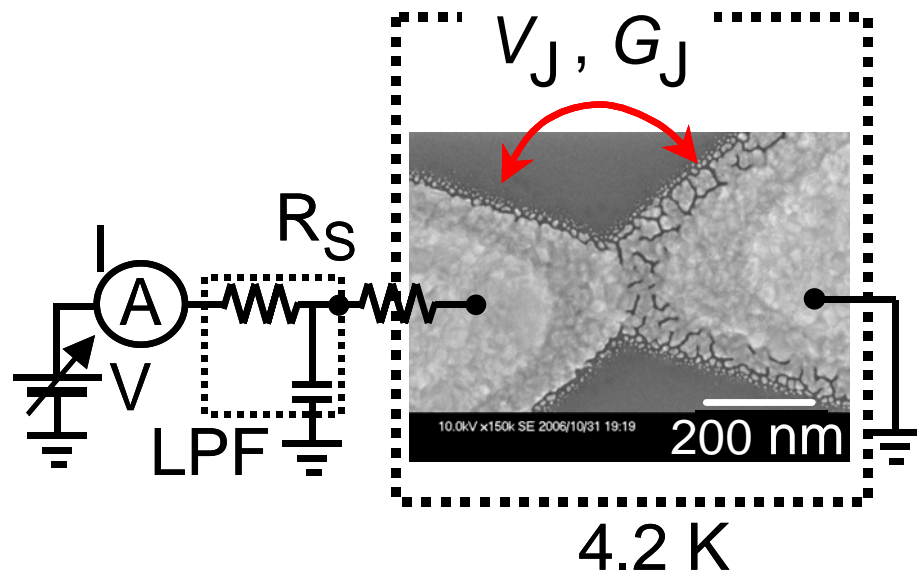


SEM image of the samples

## Shadow Evaporation

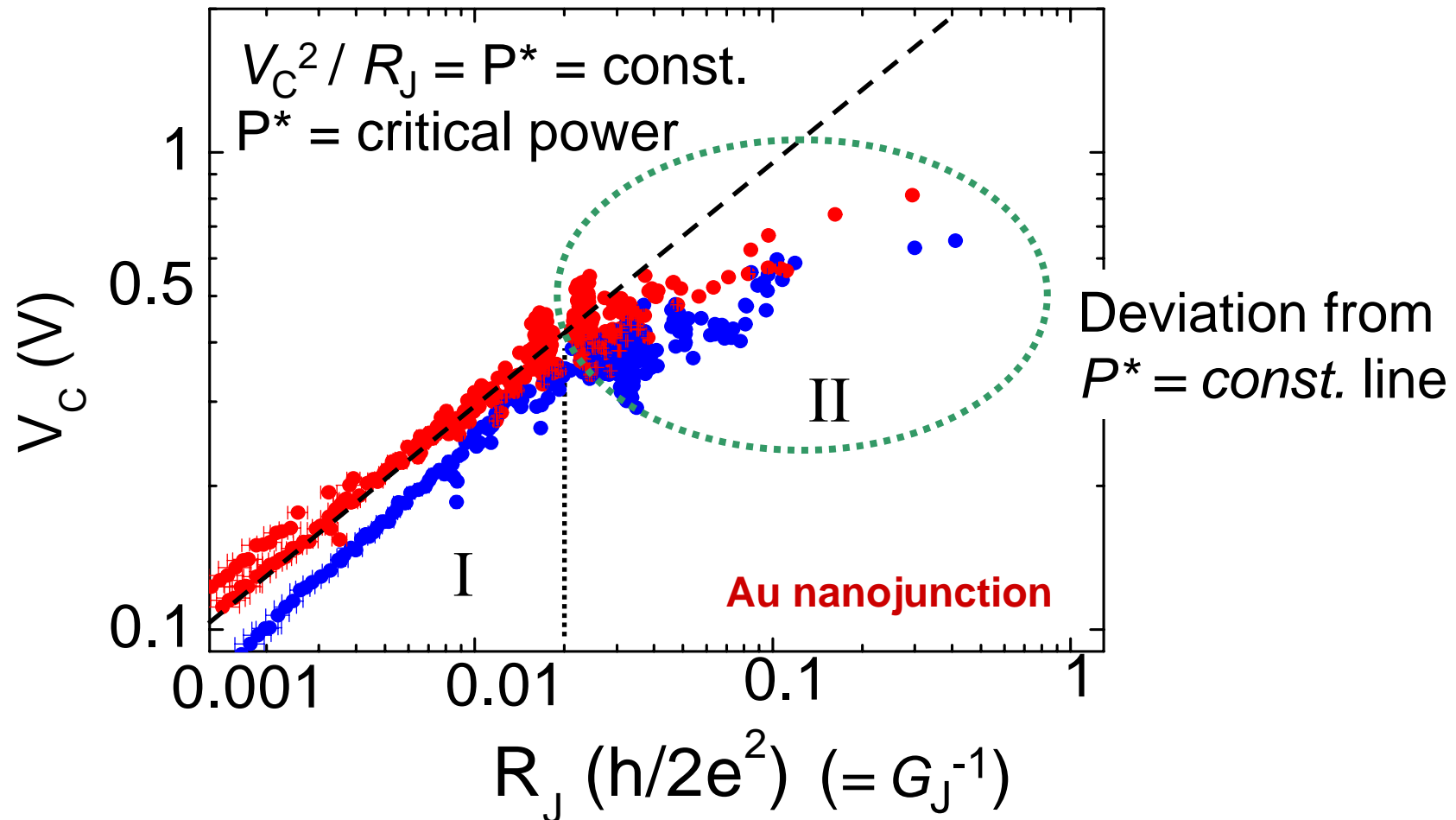


# “Feedback-Controlled” Electrical Break Junction



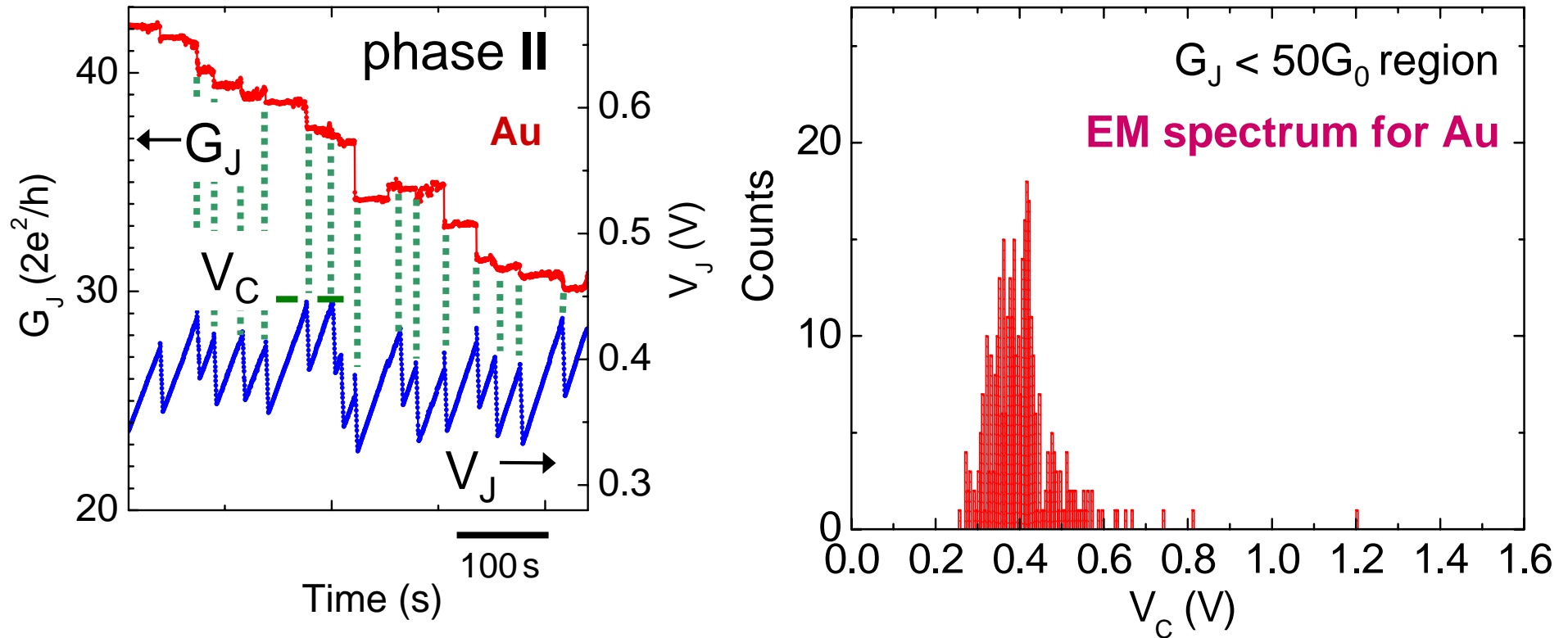
- Feedback control of EM D. R. Strachan *et al.* Appl. Phys. Lett. **86**, 043109 (2005)  
Sharp decreases in  $G_J$  (sign of EM)  $\rightarrow$  reduce  $V$
- Peak  $V_J = V_C$  (critical voltage)

# Semi-classical and Ballistic Regimes in EM



- Joule heating dominant for  $G_J > 50 G_0$  (Phase I)
- Deviation from the  $P^* = \text{const.}$  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  $\sim G_0$

The junction is in the ballistic regime (QPC)

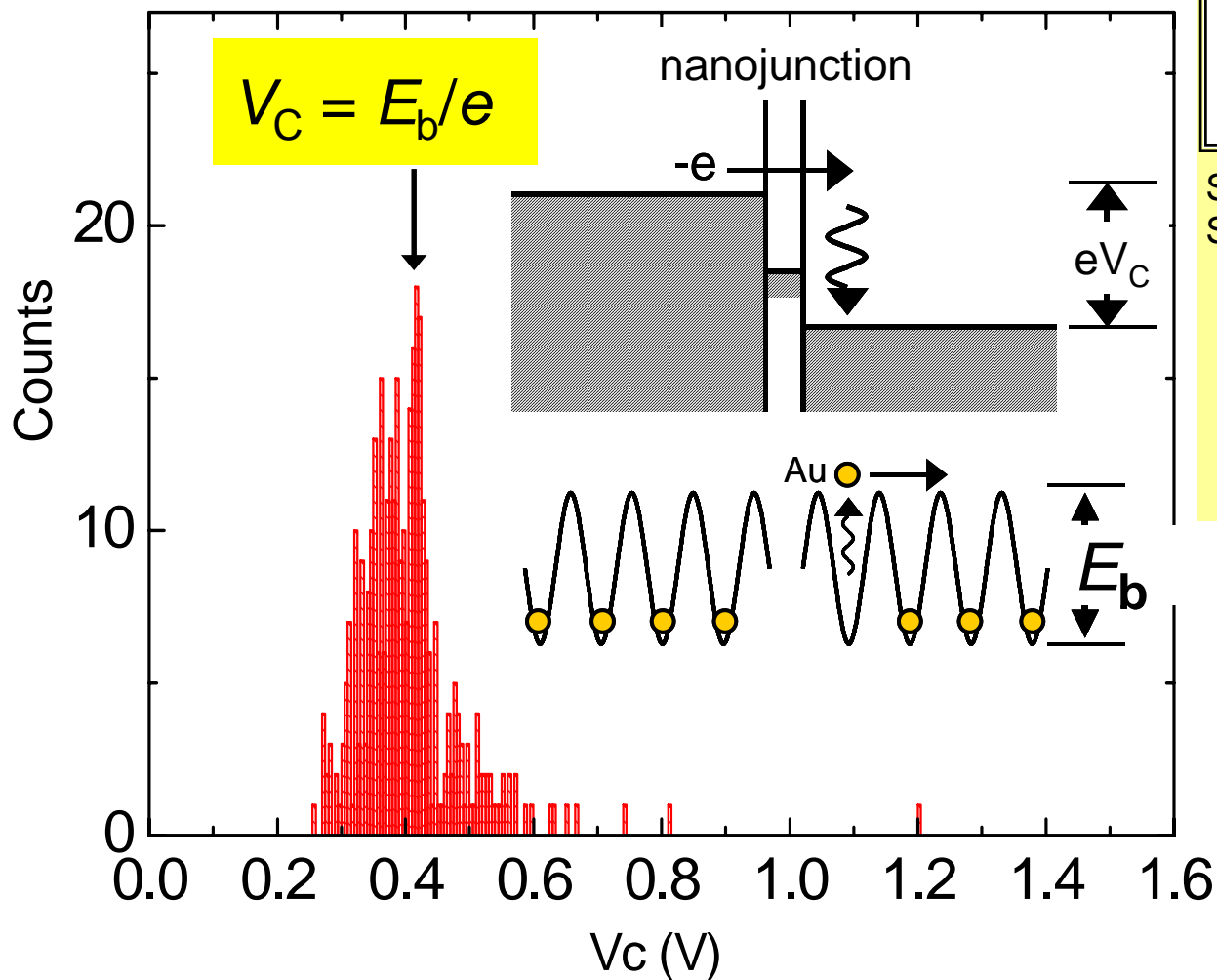
One-by-one removal of atoms from the junction

■ Histogram of  $V_C$

→ “EM Spectroscopy” (spectroscopy of atom removal events)

# EM-Spectroscopy for Au Nanojunction

## - Elementary Process of EM -



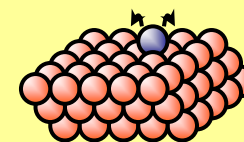
Surface diffusion  
potential:  $E_b$

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

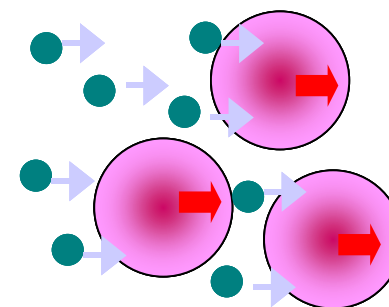
For gold

$$E_b = 0.4-0.44\text{eV}$$

STS measurement



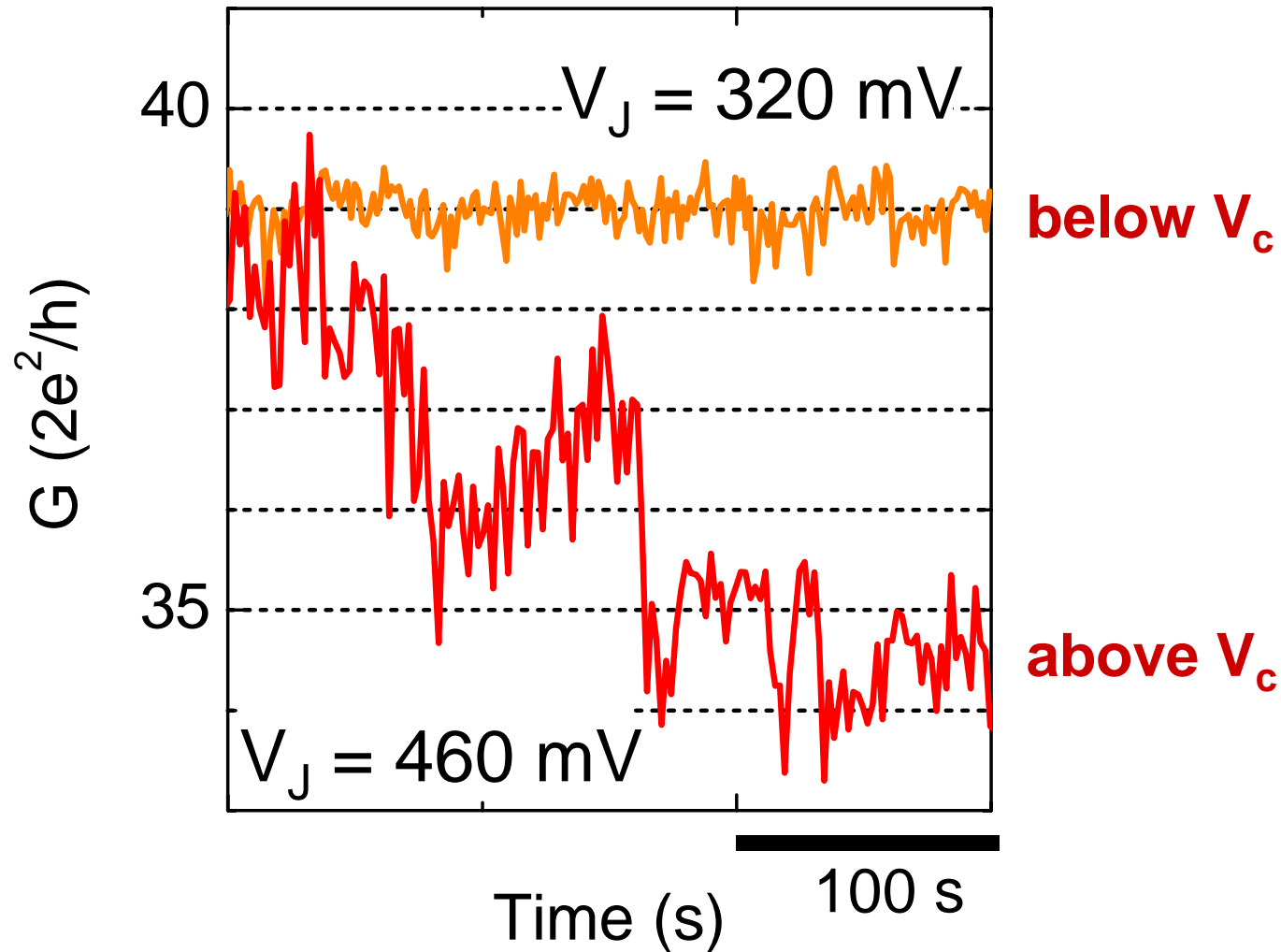
Conventional picture  
*e-wind force*



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

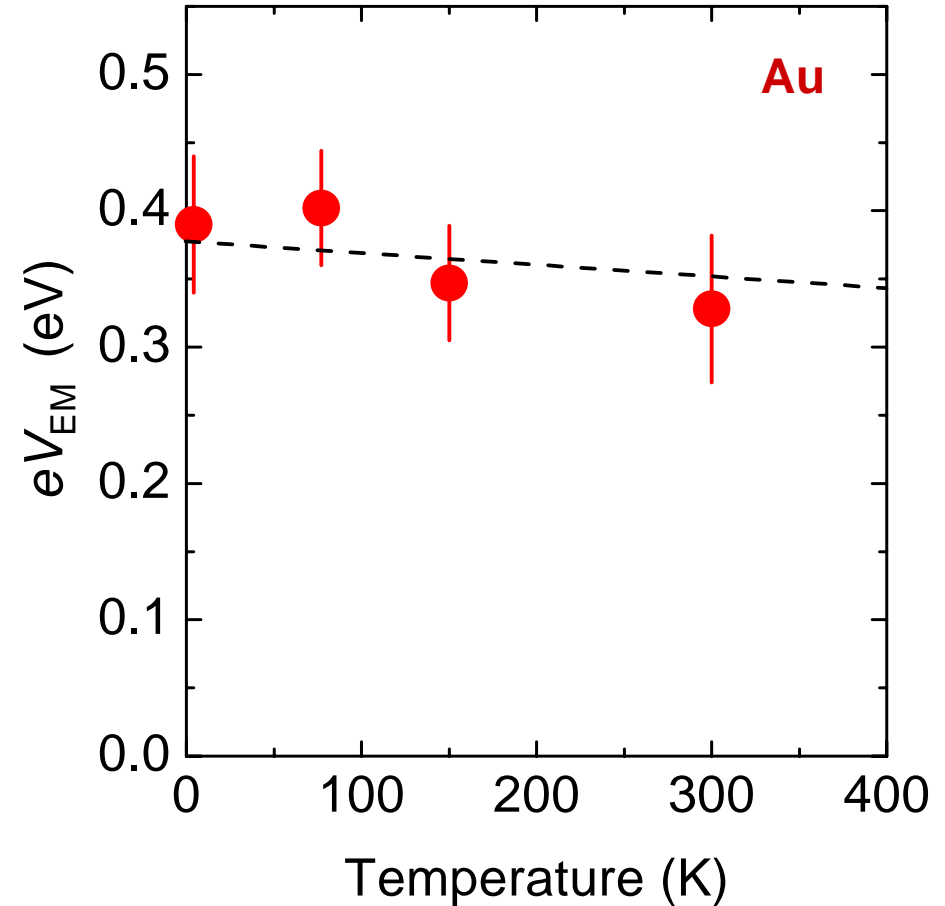
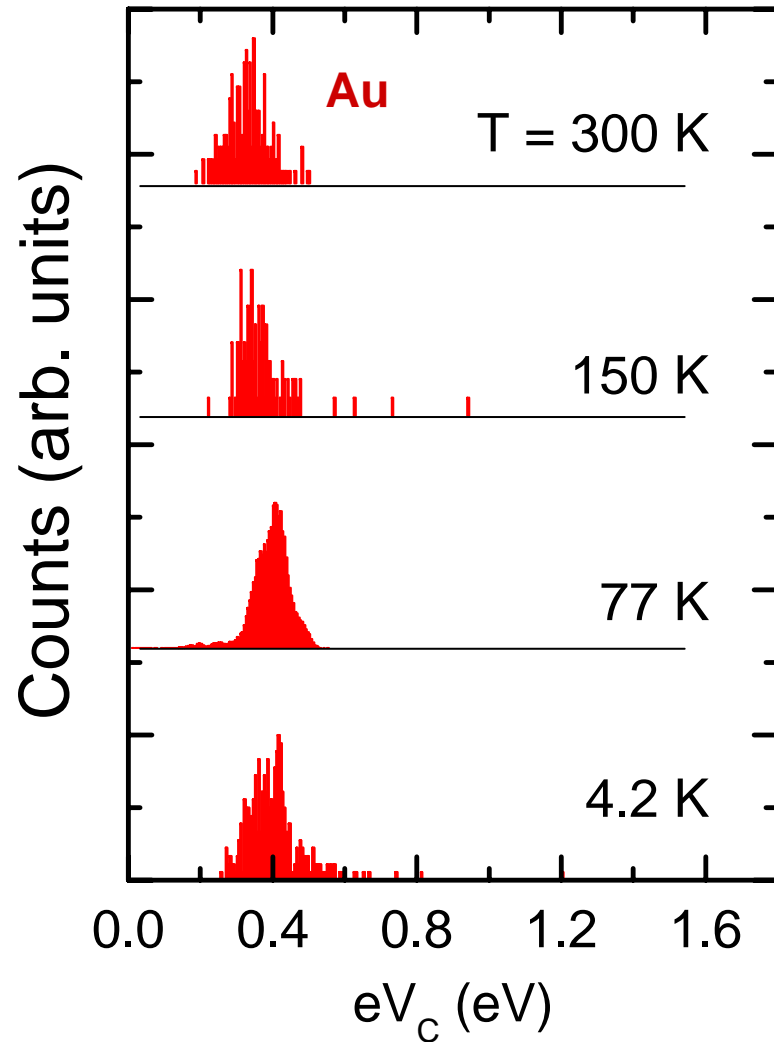
EM in the ballistic regime is induced by kinetic energy transfer from a single electron to a single atom.

## Critical Voltages for EM



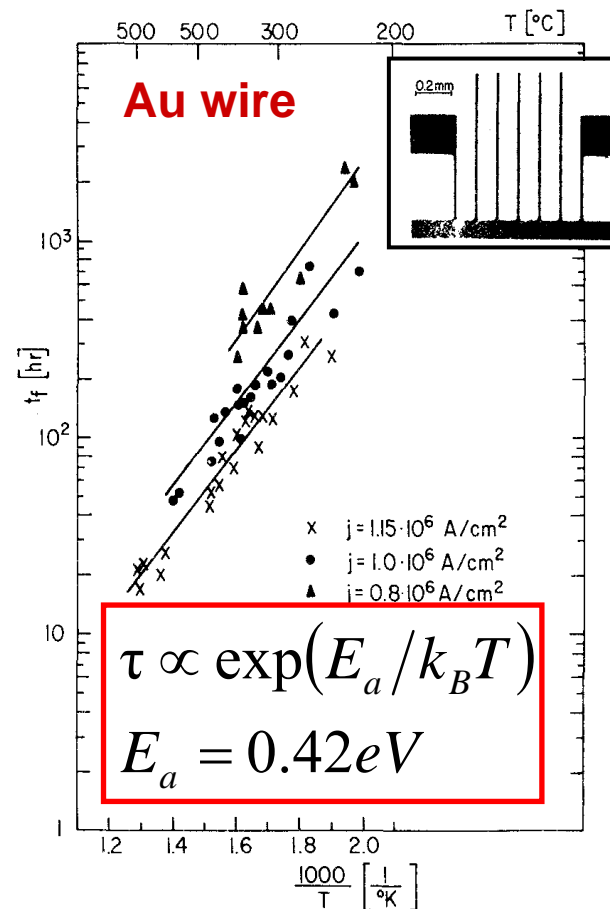
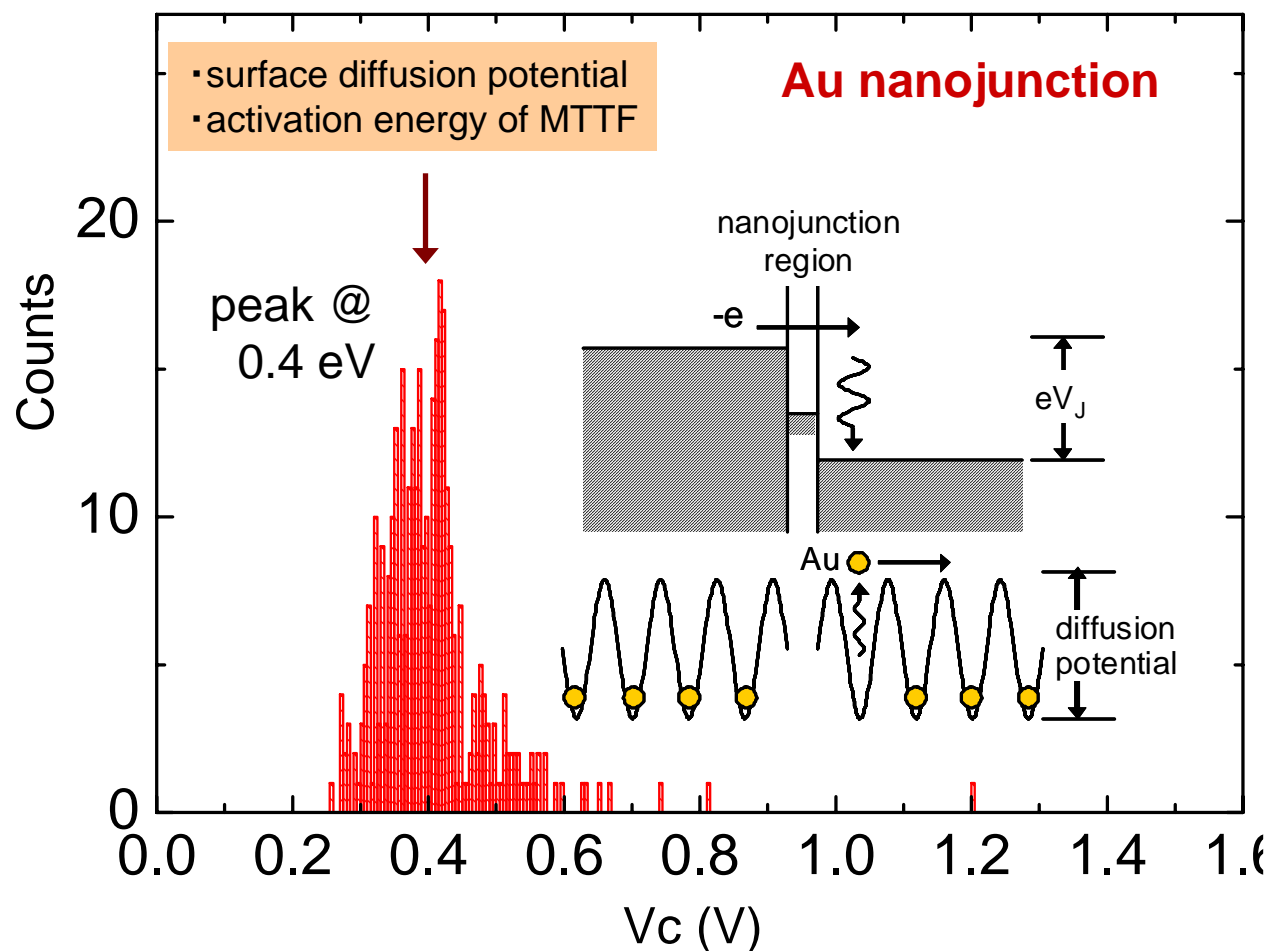
EM does not develop unless  $V_J$  exceeds the critical voltage  $V_c (= E_b/e)$ .

# Critical Voltage in the Ballistic Regime



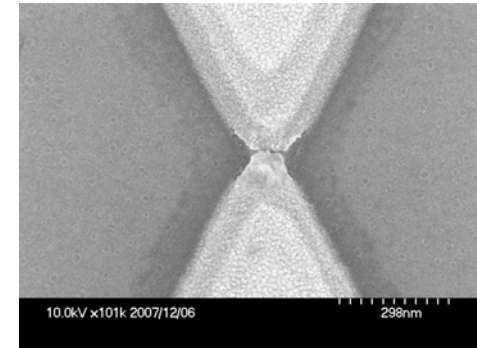
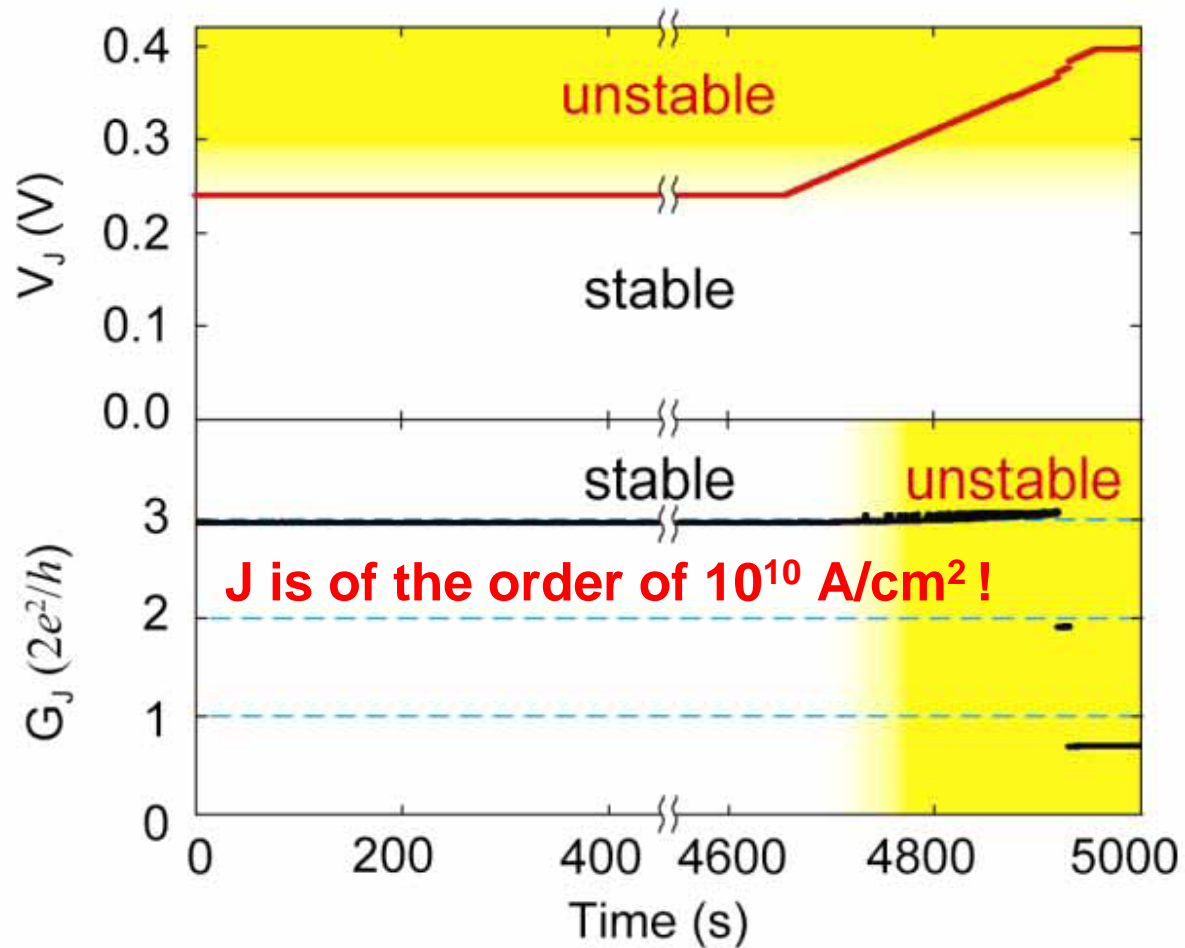
Almost no temperature dependence was observed in the EM spectrum.

# Technological Implication of EM Spectra



- 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 ( $V_C \sim 0.3$ 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  $10^{10}$  A/cm<sup>2</sup>, 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<sup>2</sup>, as long as  $V_J < V_C$ .

■ Scientific/technological implications

- ◆ Reliability of VLSI interconnections

