Fabrication of Nanogaps Using Field-Emission-Induced Electromigration with Alternating Current Bias

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1. Introduction: Field-Emission-Induced Electromigration (Activation)

➢ **Facile Preparation of Nanogaps Is an Important Issue for Fabricating Novel Functional Nanoscale Devices.**

■ **Activation: Simple Method for Fabrication of Nanogaps with Well-Controlled Tunnel Resistance**
S. Kayashima et al., *Jpn. J. Appl. Phys.* 46 (2007) L907. S. Kayashima et al., *J. Phys. Conf. Ser.* 100 (2008) 052022. Y. Tomoda et al., *J. Vac. Sci & Technol.* B 27 (2009) 813.

✓ Fabrication of Planar-Type Ferromagnetic Nanogaps with Ni/ Vacuum/ Ni Tunnel Junctions
Y. Tomoda et al., *IEEE Trans. Mag.* 45 (2009) 3480. Y. Tomoda et al., *J. Phys. Conf. Ser.* 200 (2010) 062035. T. Watanabe et al., *J. Appl. Phys.* 109 (2011) 07C919.

✓ Fabrication and Integration of Single Electron Transistors (SETs)
W. Kume, Y. Tomoda, M. Hanada, and J. Shirakashi, *J. Nanosci. Nanotechnol.* 10 (2010) 7239. S. Ueno, Y. Tomoda, W. Kume, M. Hanada, K. Takiya, and J. Shirakashi, *J. Nanosci. Nanotechnol.* 11 (2011) 1

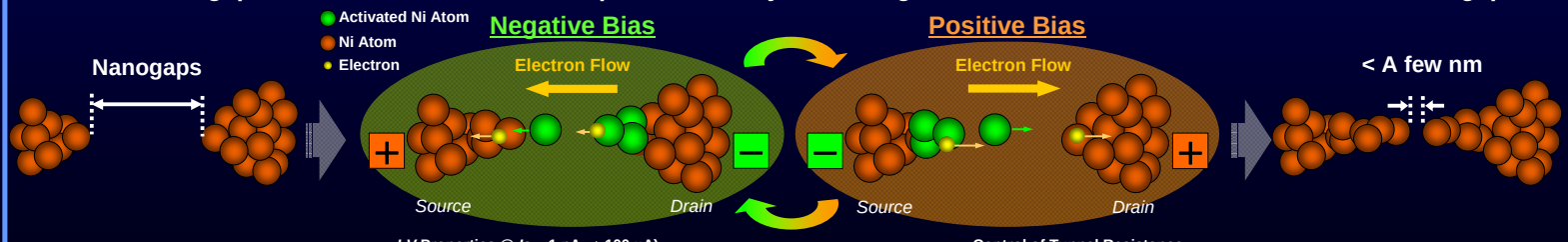
✓ Successive Control of Nanogaps by Directly Adjusting Field Emission Current with Current Source
K. Takiya, Y. Tomoda, W. Kume, S. Ueno, T. Watanabe, and J. Shirakashi, *Appl. Surf. Sci.* (2011) in print.

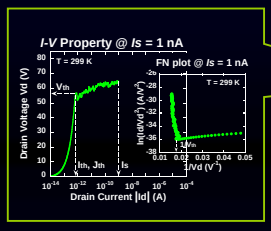
→ It Is Expected That Sharper Shape of Nanogaps Can Be Obtained by Alternating Transfer of Atoms across Gap.

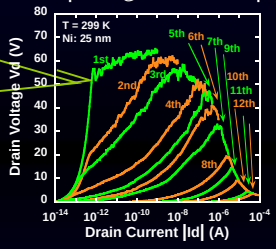
➢ **Nanogap Formation Method Controlled by Alternately Biased Activation Is Studied in Detail.**

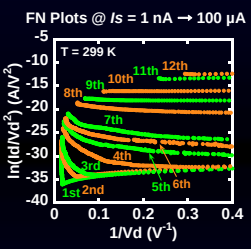
2. Alternately Biased Activation

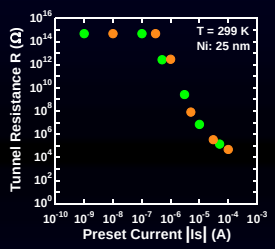
① Initial Nanogaps ② Repeat of Polarity-Reversing Procedures ③ Final Nanogaps









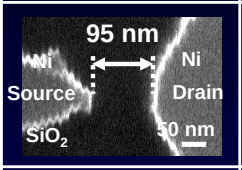
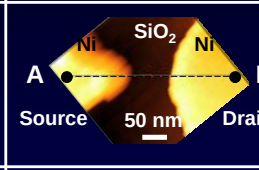
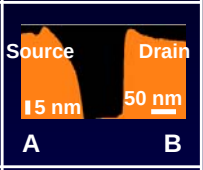
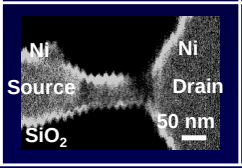
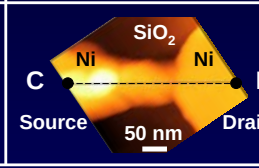
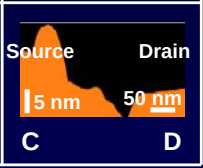


< This Study >
- Alternately Biased Activation
  R: > 100 TΩ → 48 kΩ
  @ *Is* = 1 nA ~ 100 μA

< Our Previous Work >
- Current-Source-Based Activation
  K. Takiya et al., Appl. Surf. Sci. (2011) in print.
  R: > 100 TΩ → 70 MΩ
  @ *Is* = 1 nA ~ 3.5 μA

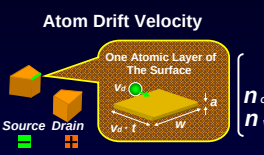
- Remarkable Decrease in Field Emission Current → Decrease of Gap Separation
- Successive Control of Tunnel Resistance of Nanogaps → Improvement of Stability of Nanogaps Formation Process

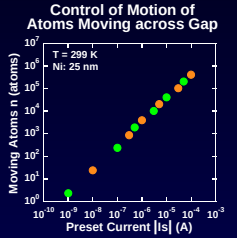
3. SEM and AFM Images of Nanogaps

	SEM	AFM	AFM
BEFORE Activation (Initial Nanogap)			
AFTER Activation (@ *Is* = 100 μA)			

- Self-Regulation of Gap with Final Spacing by Applied Current
  → Enhancement of Stability during Formation of Nanogaps

4. Number of Moving Atoms: $n_{Current}$





$$n_{Current}\ (\text{atoms}) = V \cdot N = (w\,a\,v_d\,t) \cdot N = 5.8 \times 10^{7} \cdot \int i\,dt$$

- **Atom Drift Velocity: $n_{Current}$ = 10^5 (atoms)**
  I. A. Blech et al., *Thin Solid Films*. 25 (1975) 327.
- **SEM Image: $n_{Current}$ = 10^6 (atoms)**
- $\frac{1}{n_{Current} \cdot e} \Sigma Q = 10^{11}$ (electrons/atom)

→ $n_{Current} \fallingdotseq n_{Voltage}$
Y. Tomoda et al., *J. Vac. Sci & Technol.* B 27 (2009) 813.

5. Conclusions

■ **Successive Control of Tunnel Resistance *R* of Nanogaps Using Alternately Biased Activation**
✓ Tunnel Resistance *R*: 100 TΩ → 48 kΩ @ Preset Current *Is*: 1 nA → 100 μA

■ **Decrease of Gap Separation Observed by SEM and AFM Images Before and After Alternately Biased Activation**
✓ Gap Separation *W*: 95 nm → < A few nm @ Preset Current *Is*: 1 nA → 100 μA

■ **Estimation for Number of Moving Ni Atoms from Point of View of Atom Drift Velocity**
✓ Number of Moving Ni Atoms *n*: 10^5 atoms @ Preset Current *Is*: 100 μA
→ Stable Control of Motion of Atoms Moving across Gap by Magnitude and Direction of Field Emission Current

Alternately Biased Activation Can Improve Stability and Controllability during Formation of Nanogaps.