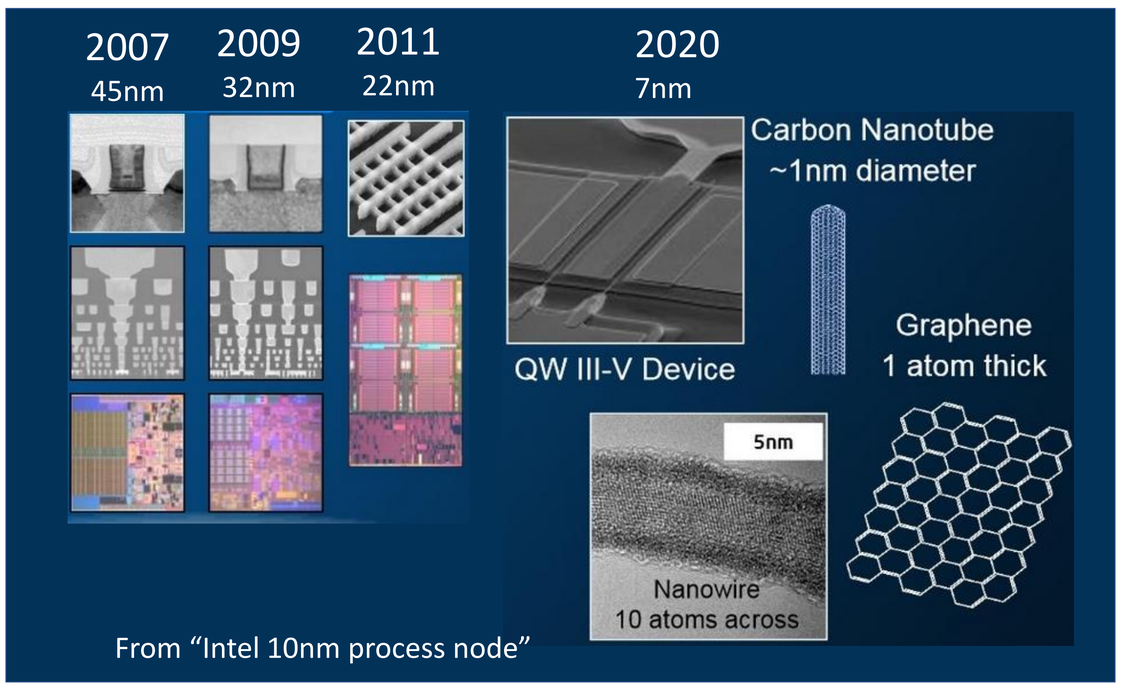
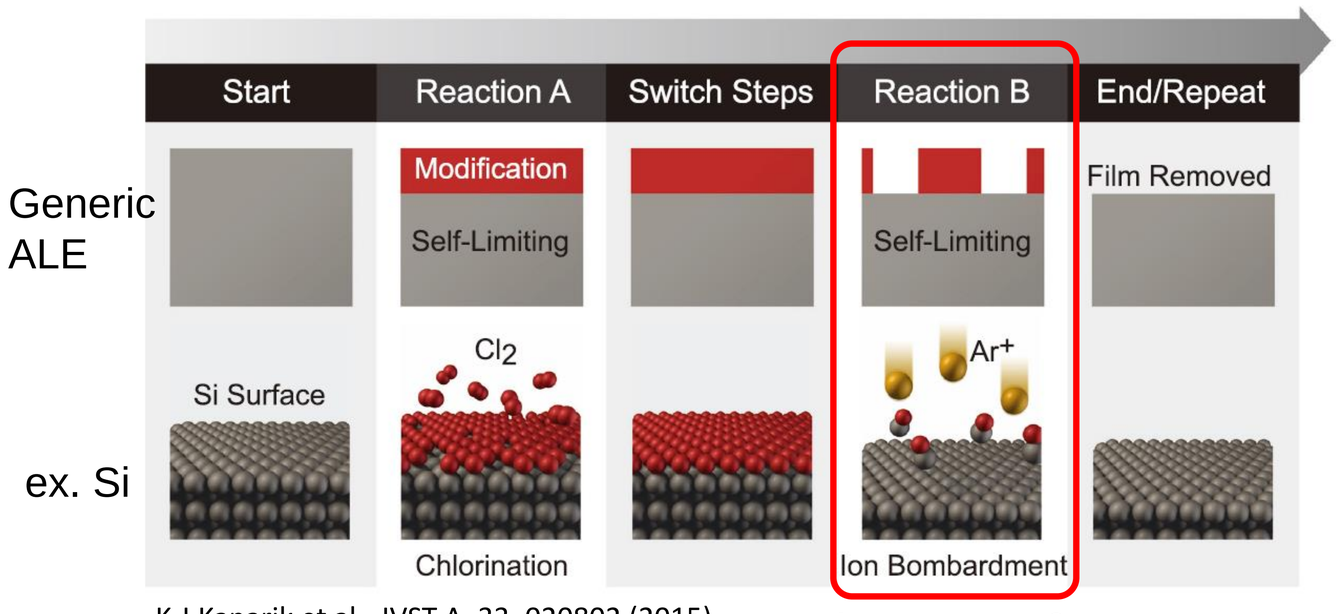
Atomic Layer Etching with Gas Cluster Ion Beams

Abstract

We will introduce atomic layer etching (ALE) using gas cluster ion beam (GCIB), which is ultra low-energy ion beam of several eV/atom. By repeating self-limiting following process, (1) adsorption of reactive gas, (2) evacuation of residual gas, and (3) removal of surface layer with GCIB bombardment, low-damage and low-temperature ALEs are realized. In this study, halogen free ALE for metals are studied using acetic acid gas & GCIB irradiations.

Motivation of study



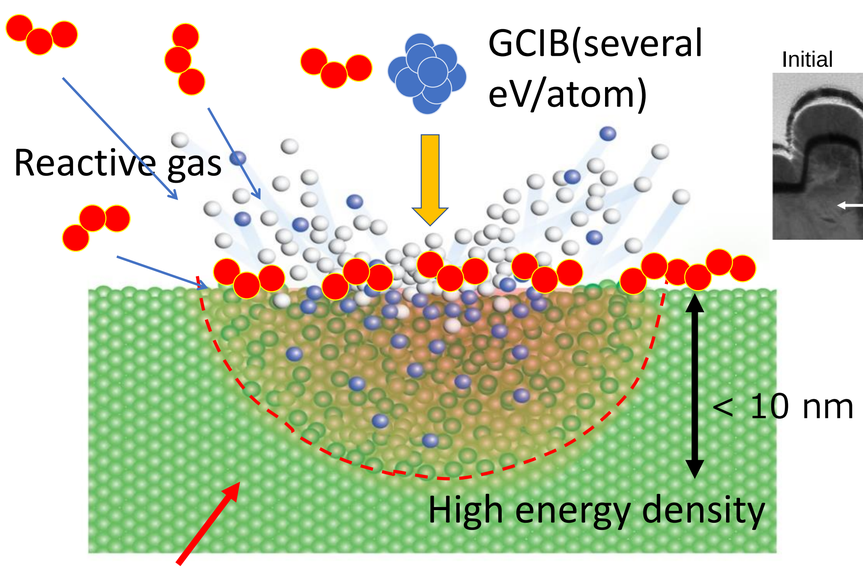


K.J.Kanarik et al., JVST A, 33, 020802 (2015)

Low temp. & Low-damage ?

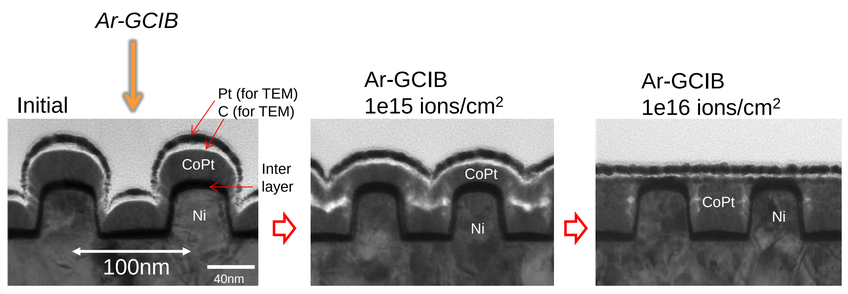
With the miniaturization of devices and development of 2D materials, atomic layer etching (ALE) attracts many attentions. In ALE, etching proceeds by repeating the self-limiting adsorption, evacuation of residual gas and self-limiting removal by ion bombardment. For removal process, low-temp. & low-damage are required. In this study, GCIB is employed for the atomic removal process for the first time.

Characteristics of Gas Cluster Ion Beam (GCIB)

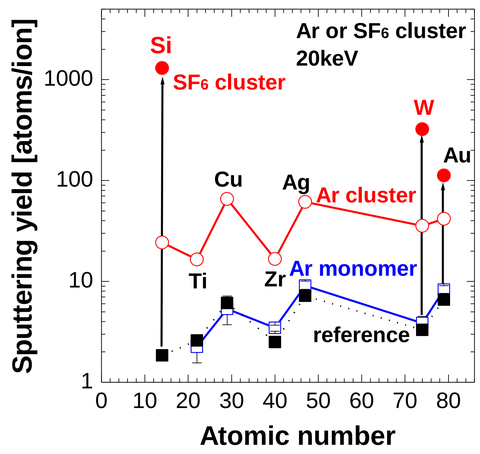


Transient heating by GCIB bombardment

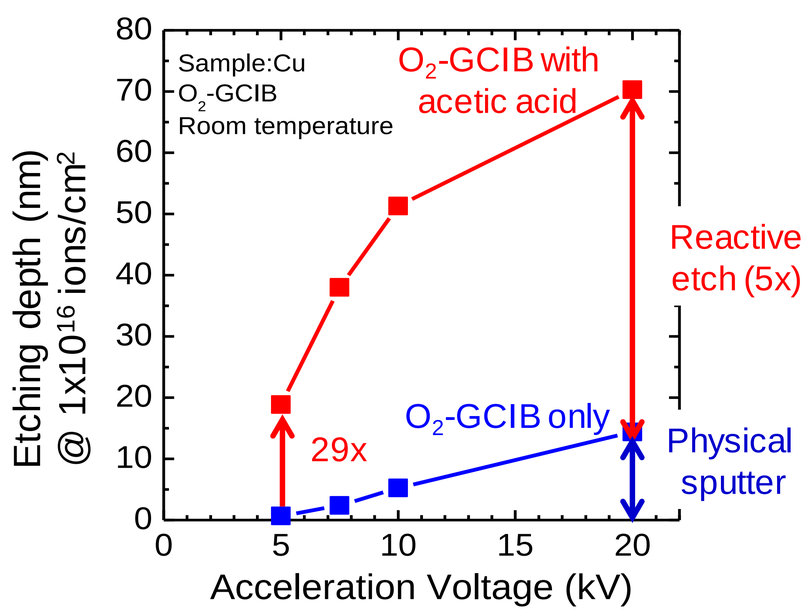
Substrate is at room temp.
→ Adsorption of reactive gas on surface



Surface smoothing

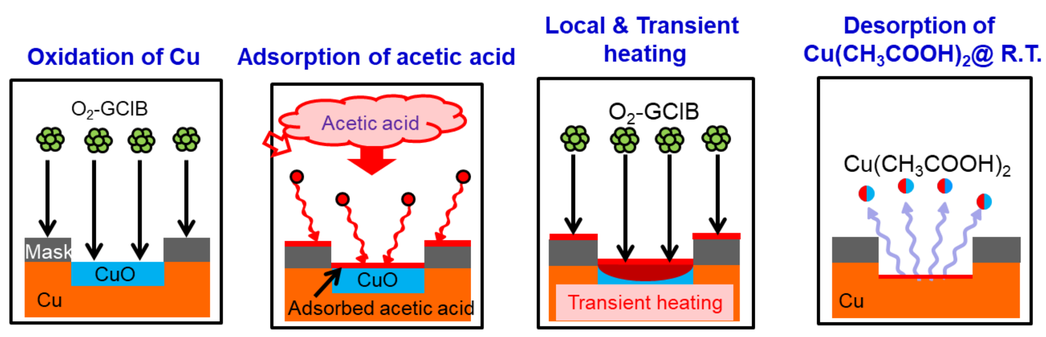


Reactive sputtering



Cu etching depth by O_2-GCIB irradiation with acetic acid vapor.

GCIB is a giant particle with thousands of gaseous atoms bonded with Van der Waals force. It realizes ultra low-energy (several eV/atom), however, it also induces high energy density near the surface. These unique irradiation effects enhance the chemical reactions at low-tempearure without irradiation damage, which is ideal for ALE.



$CuO + 2CH_3COOH \rightarrow Cu(CH_3COO)_2 + H_2O$

200°C Non volatile (BP 240°C)

Cu etching by O_2-GCIB with acetic acid adsorption

T. Suda et al, Jpn. J. of Appl. Phys, 51(2012), 08HA02

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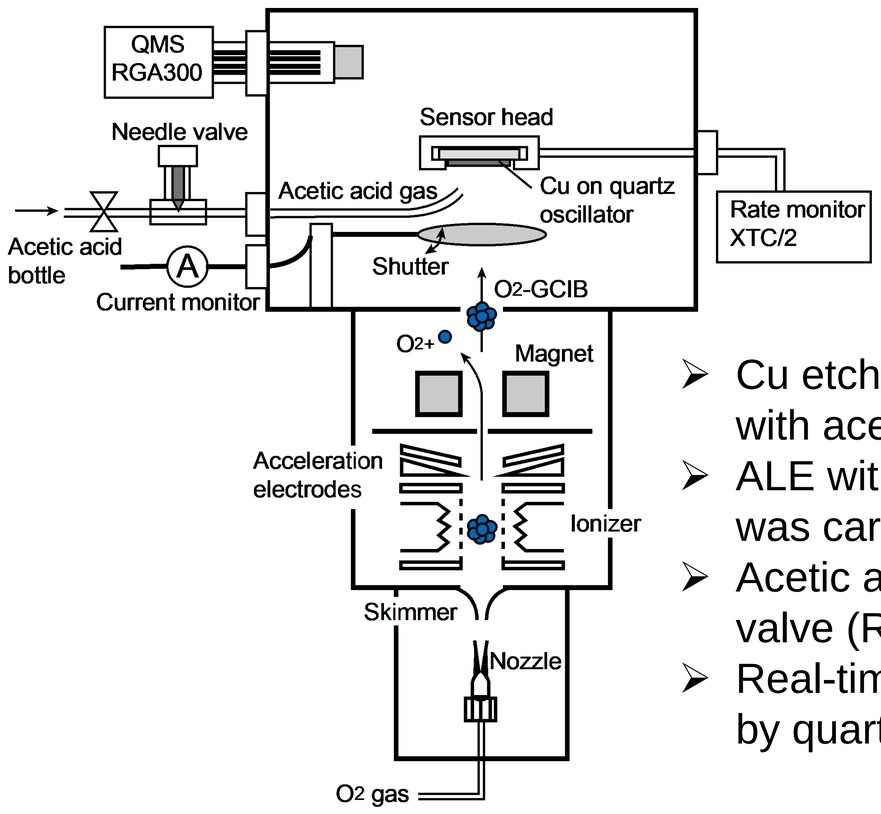
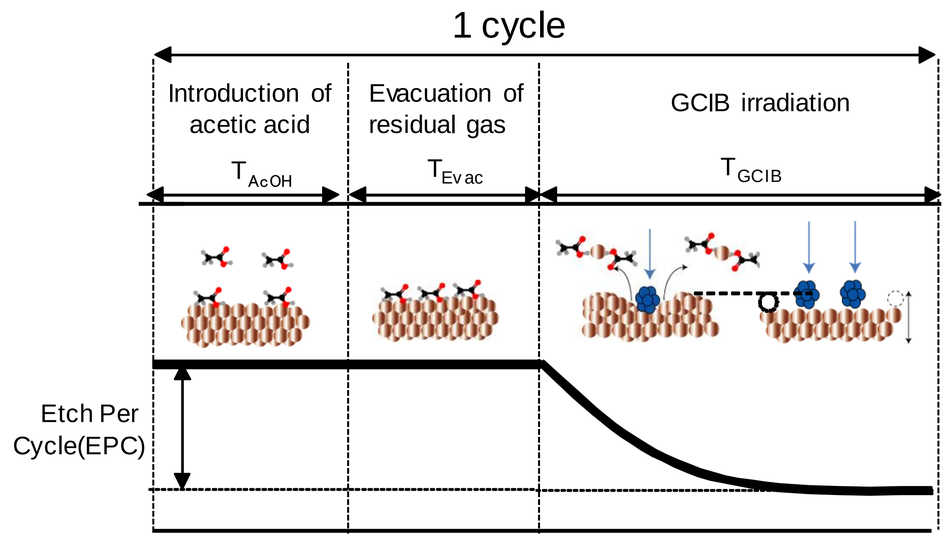
GCIB equipment & Experiment



Configuration of GCIB-ALE equipment

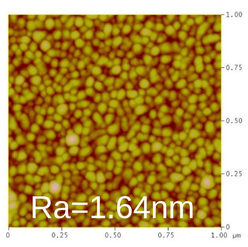
- Cu etching by continuous GCIB with acetic acid had reported.
- ALE with acetic acid & O_2-GCIB was carried out for the first time
- Acetic acid supply with a needle valve (RGA monitor)
- Real-time thickness monitoring by quartz crystal microbalance



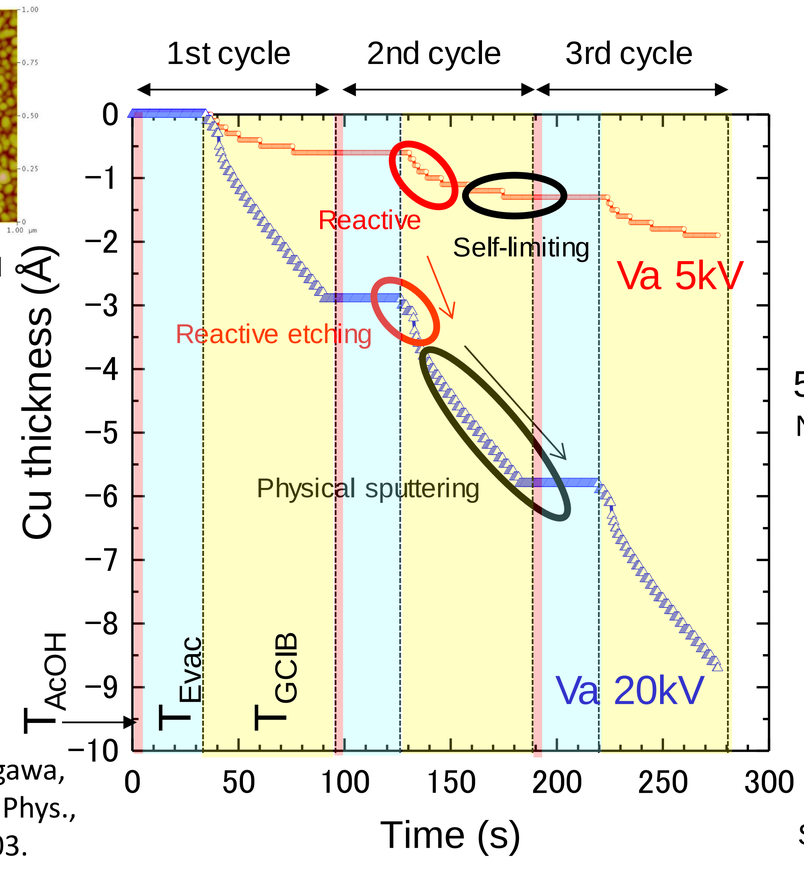
GCIB-ALE conditions

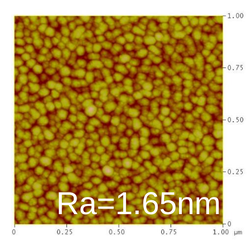
- O_2-GCIB (size: 2500 molecule/atom)
  → Cu films on QCM
- Acetic acid partial pressure: 2e-3 Pa
- Accel. voltage: 5 – 20 kV (2 ~ 8eV/molecule)
- Subst. temp.: Room temp. (water cooling)
- T_{AcOH} (5 s), T_{evac} (30 s), T_{GCIB} (60 s)

GCIB-ALE of metals with acetic acid vapor

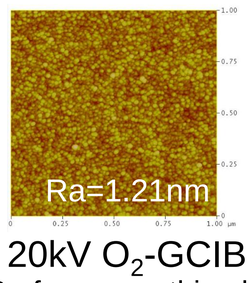


Pristine Cu





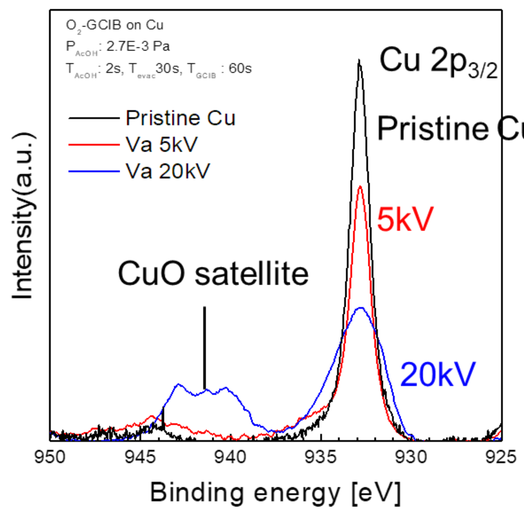
5kV O_2-GCIB
No smoothing due to chemical reactions



20kV O_2-GCIB
Surface smoothing by physical sputtering

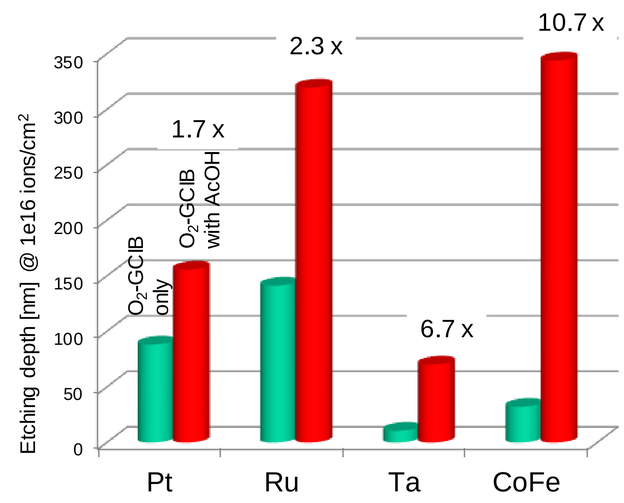
N. Toyoda, A. Ogawa, J. Phys. D: Appl. Phys., **50** (2017) 184003.

Cu thickness variation by GCIB-ALE (5 & 20 kV)



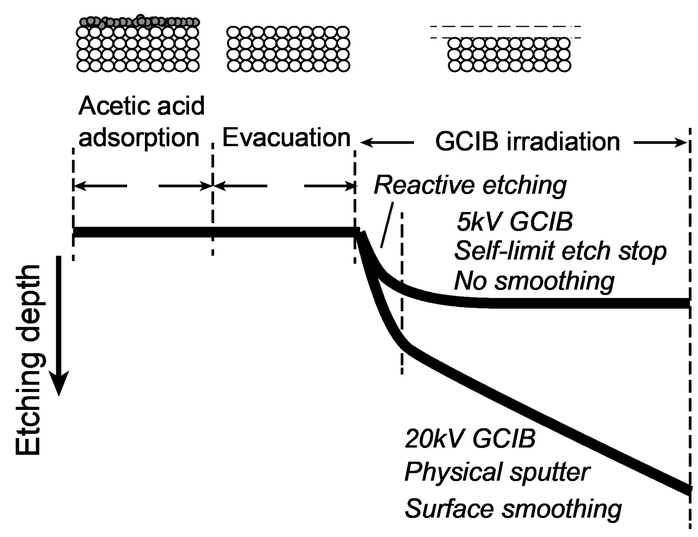
Cu XPS after GCIB-ALE

Cu is oxidized by 20kV O_2-GCIB. These oxide is removed by 5 kV O_2-GCIB ALE



Metal etching by O_2-GCIB with acetic acid

Various metals (Pt, Ru, Ta, CoFe) can be etched by O_2-GCIB with acetic acid vapor.



GCIB-ALE

- Near atomic layer of Cu (< 1 nm) was etched by 5 kV O_2-GCIB with acetic acid. Self-limit etch stop.
- Physical sputtering @ 20 kV O_2-GCIB (not self-limiting. Surface smoothing & oxidation occurs)
- Various metals (Pt, Ru, Ta, CoFe), which is difficult to etch can be processed by GCIB-ALE.

Summary

✓Halogen free, Low damage & Low-temp. ALE with 5keV O_2-GCIB(~2eV/molecule) was demonstrated.
✓GCIB-ALE can be applied for various metals.
✓Applications for STT-MRAM, 2D materials etc.

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