Nanometer Scale Patterning and Processing

Spring 2016

Lecture 29

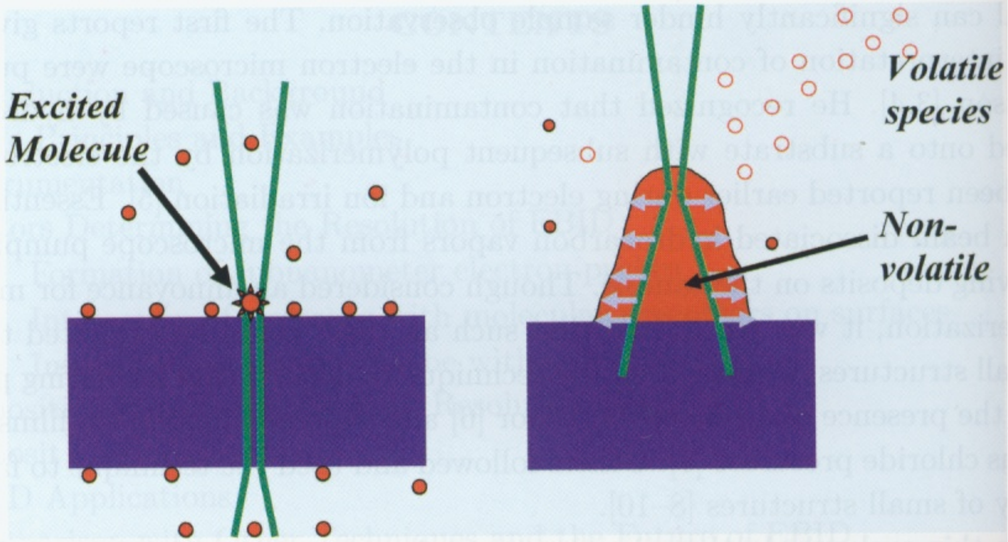
Focused Electron Beam Induced Deposition and Deposition Rate

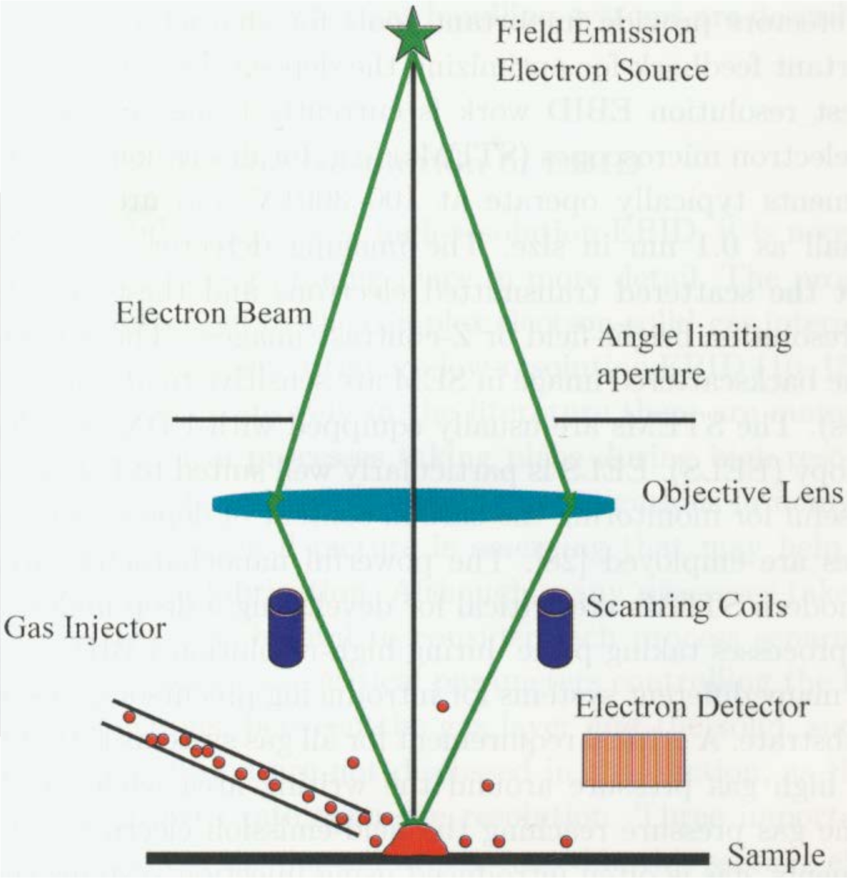
Focused ion beam (FIB)

1. Focused ion beam induced deposition.
2. Focused electron beam induced deposition.
3. Deposition rate (electron and gas flux-limited regimes)
4. Deposit composition (carbon/metal)

Focused electron beam induced deposition

Tools: DualBeam FIB/SEM, SEM, Scanning TEM





The overall picture of deposition is similar to focused *ion* beam induced deposition:

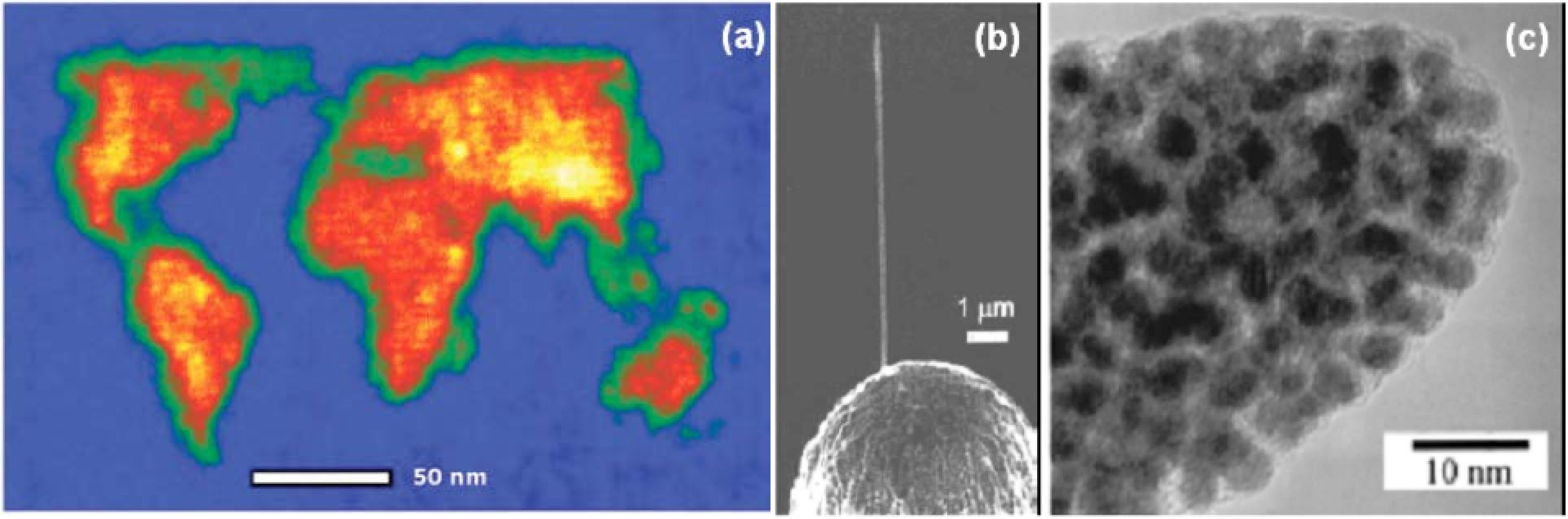
- Fast electron excites an adsorbed precursor molecule.
- Excited molecule dissociates into volatile and non-volatile components.
- The volatile component escapes and leaves behind the non-volatile deposit.

Focused electron beam induced deposition: examples

On non-flat surface with high aspect ratio

On flat surface (very high resolution)

Deposit far from being pure metal,
up to 90% impurity (mostly carbon)



a) A topographical map of the world on a flat substrate.
b) A tip grown on a scanning tunneling microscopy probe.
c) High-resolution TEM image of a typical deposit showing a nano-composite material nanometer-sized metal crystals in an amorphous C matrix.

Comparison to FIB induced deposition

- No sputtering/material removal, so always pure deposition, unless reactive gas is introduced (then form volatile species) – gas assisted FEB (focused electron beam) etching similar to gas assisted FIB etching.
- Deposit has no Ga impurity, but a lot more amorphous carbon.
- Worse electrical conductivity, more important to avoid polymerization component in the precursor gas (C-H).
- Deposition speed of FIB-ID is 10× that of FEB-ID for reasons not well understood yet.
- For low-aspect ratio deposition, FEB-ID is better for high resolution due to small focused electron beam size.
- For high aspect ratio nano-rod deposition, FIB-ID is usually better because ion-solid interaction is well localized near the rod-apex, so is the deposition.
- Application side, FIB-ID is more mature and is widely used in industry; FEB-ID is essential for DUV mask repair because Ga^+ implantation into mask blocks DUV light.

Focused ion beam (FIB)

1. Focused ion beam induced deposition.
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Deposition rate

$$\frac{dN}{dt} = gF\left(1 - \frac{N}{N_0}\right) - \sigma(E)NJ - \frac{N}{\tau}$$

dN/dt=0 at steady state

$$N = N_o\left(\frac{\frac{gF}{N_0}}{\frac{gF}{N_0} + \sigma J + \frac{1}{\tau}}\right)$$

$$R = V_{molecule} N\sigma J$$

$$R = V_{molecule} N_0 \frac{\frac{gF}{N_0}\sigma J}{\frac{gF}{N_0} + \sigma J + \frac{1}{\tau}}$$

N (cm^{-2}): precursor molecule coverage

g: sticking factor

F ($cm^{-2}s^{-1}$): gas flux arriving at the substrate

N_0: available adsorption site density in a monolayer

σ(E) (cm^2): dissociation cross section

J (electrons s^{-1} cm^{-2}): current density

τ (s): residence time

Assume $J = J_{PE}+J_{BSE}+J_{SE}$ = beam current

R(cm/sec): growth rate

$V_{molecule}$ (cm^3): volume of deposited molecule

Deposition rate: two regimes

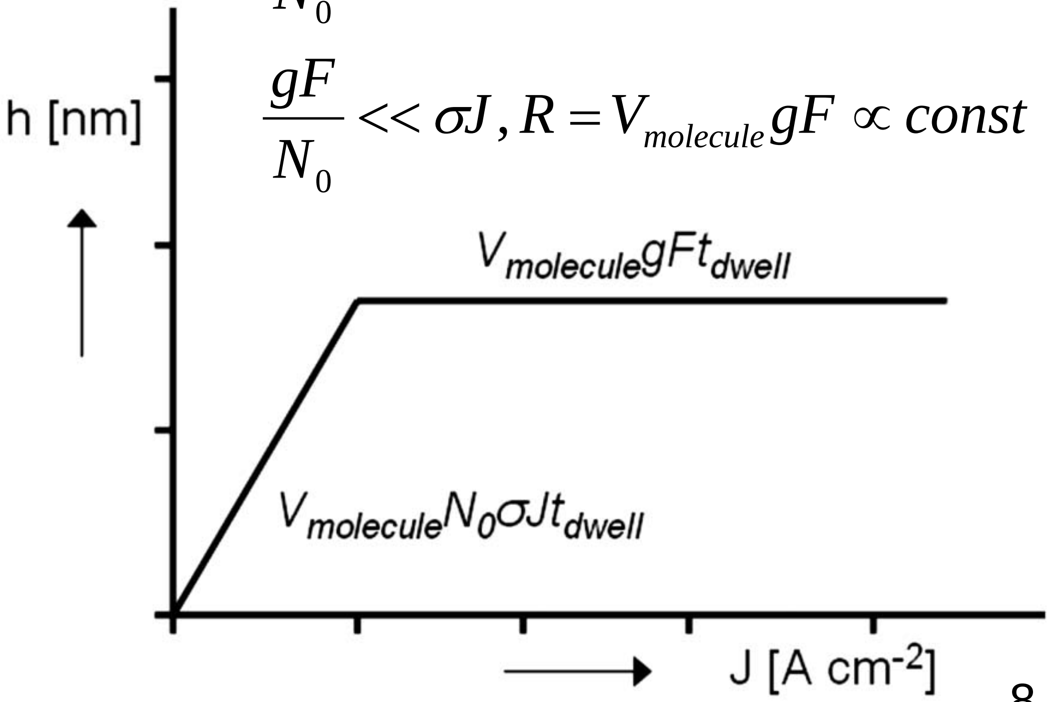
Ignore desorption (τ=∞), two regimes:

- Current limited, rate independent of gas flux.
- Gas flux limited, rate independent of current density.

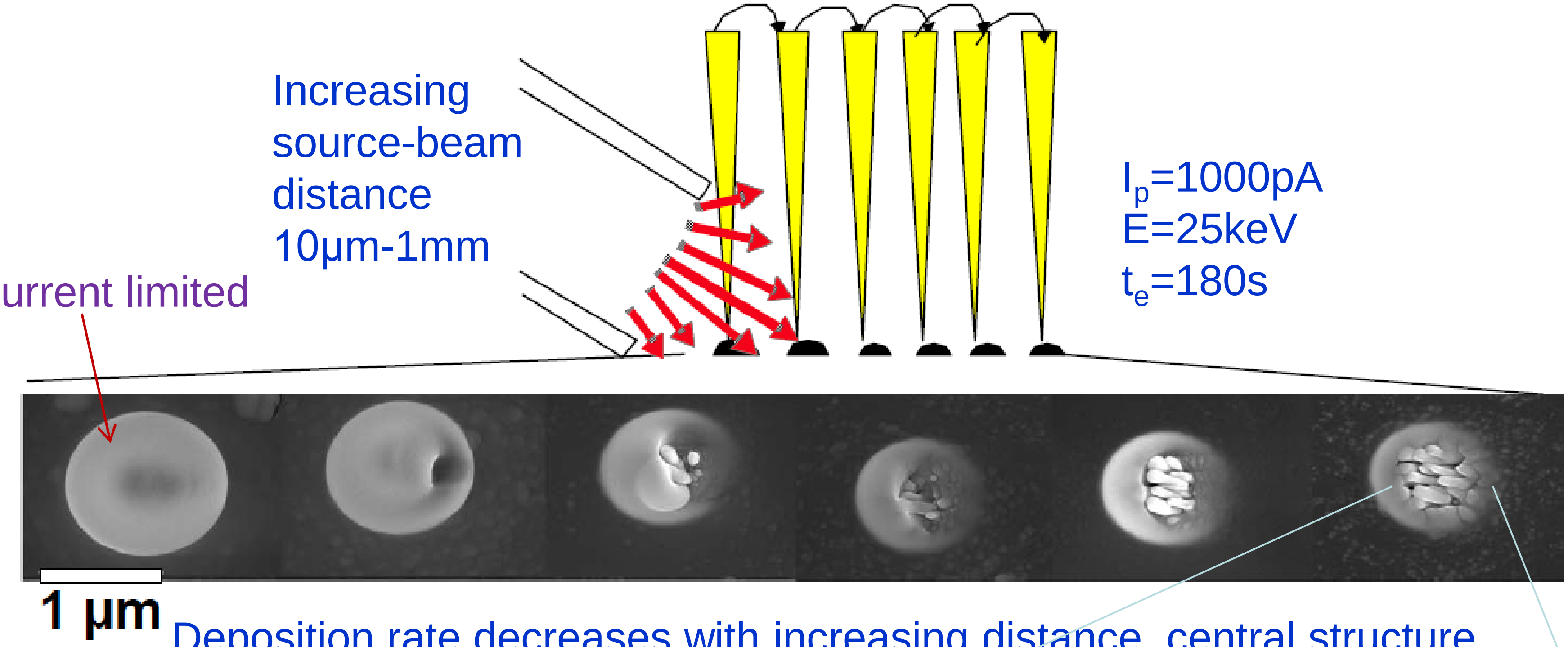
In both regimes, height increases with dwell time linearly.

$$\frac{gF}{N_0} >> \sigma J\,, R = V_{molecule} N_0 \sigma J \propto J$$

$$\frac{gF}{N_0} << \sigma J\,, R = V_{molecule}\, gF \propto const$$



Effect of precursor transport (gas flux)

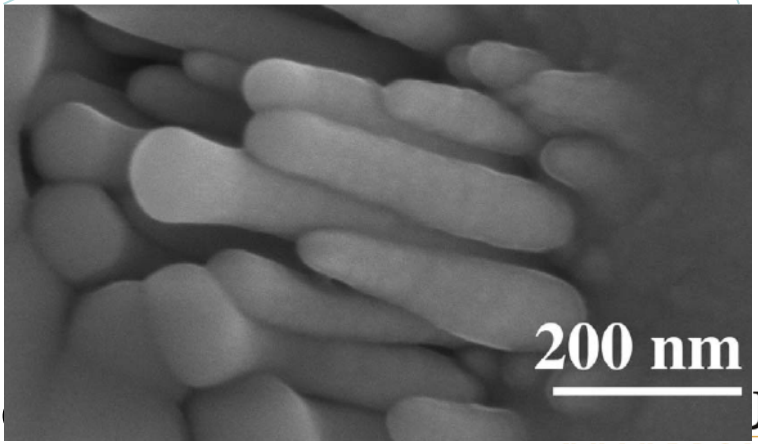


Increasing source-beam distance 10μm-1mm

Current limited

I_p=1000pA
E=25keV
t_e=180s

Deposition rate decreases with increasing distance, central structure appears

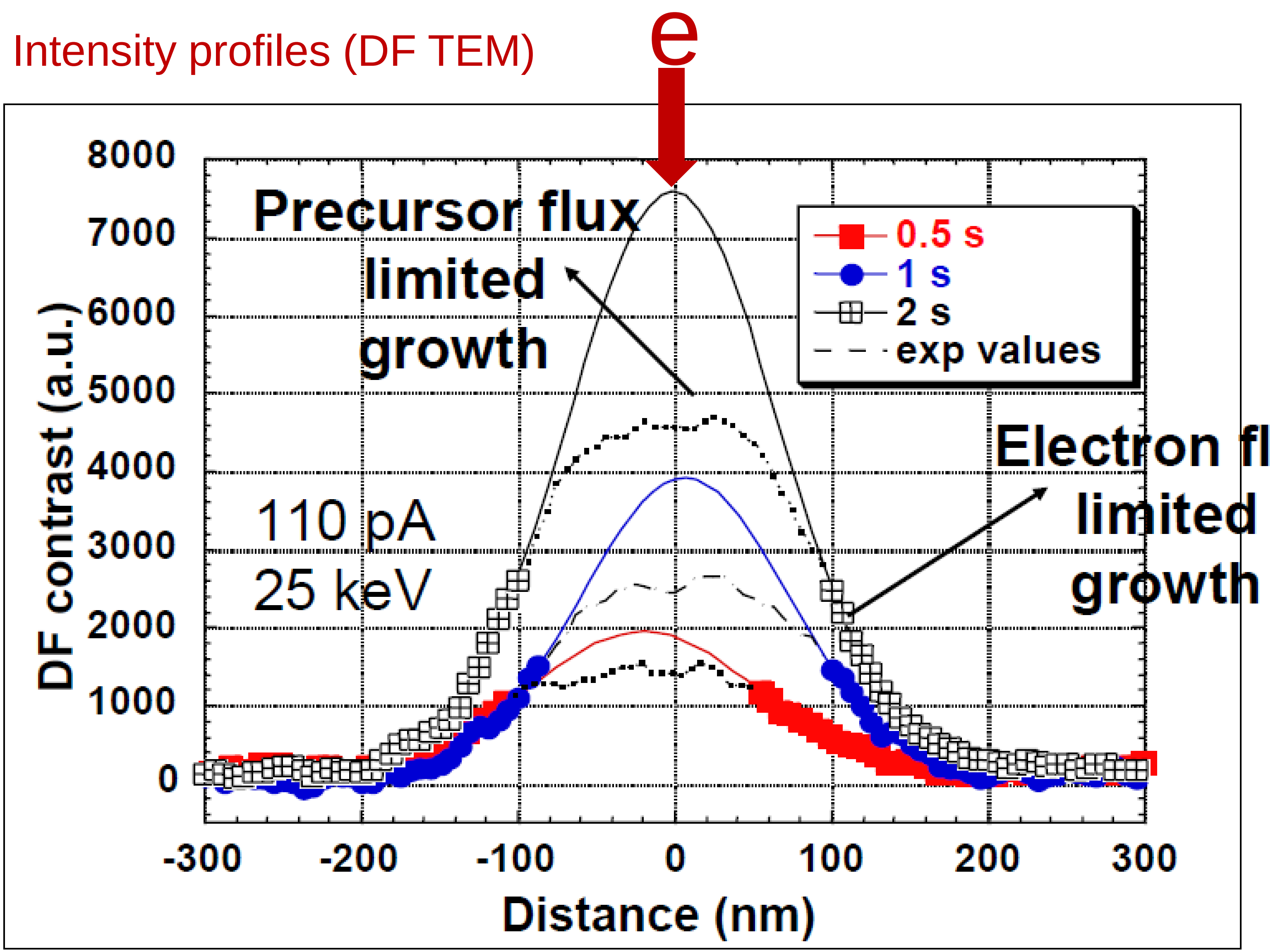


High electron density: columnar growth (beam center).

Low electron density: “polymerization” (by peripheral electrons and BSE, current-limited growth)

Deposition rate: two limiting regimes

Intensity profiles (DF TEM)



Deposition diameter

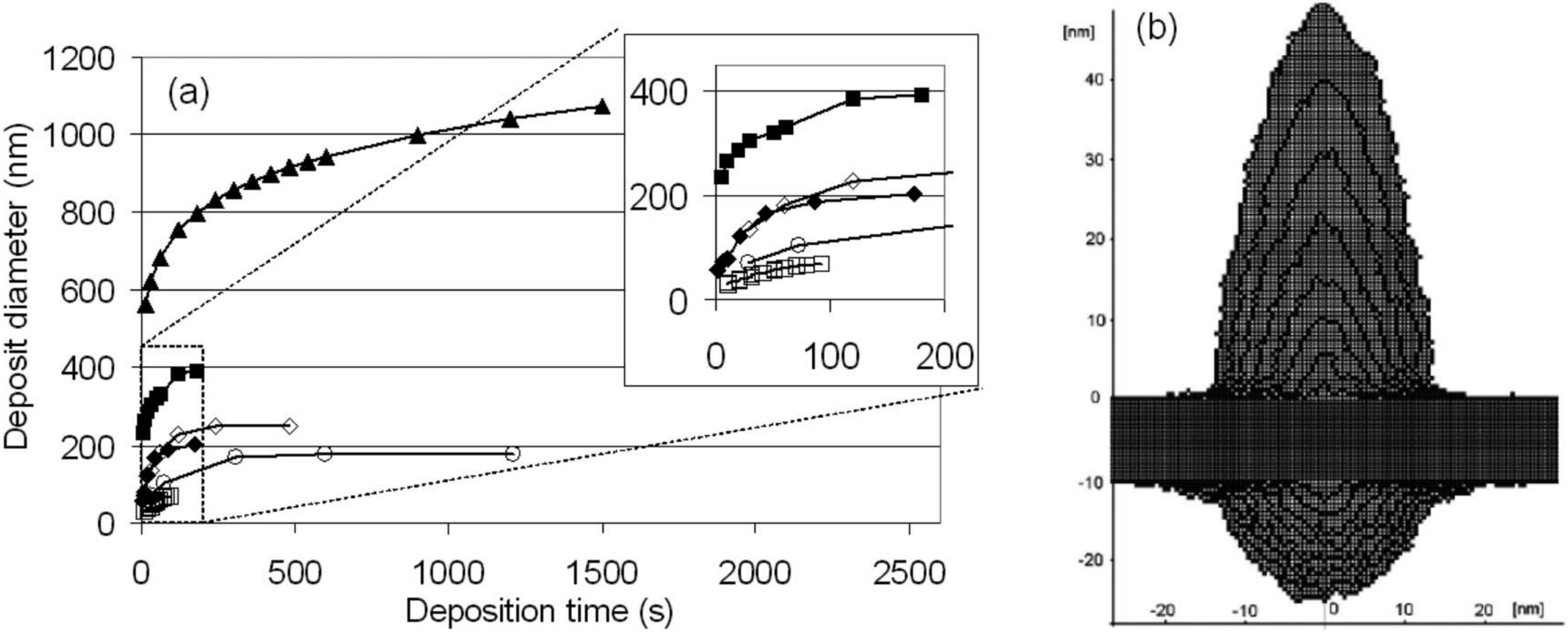
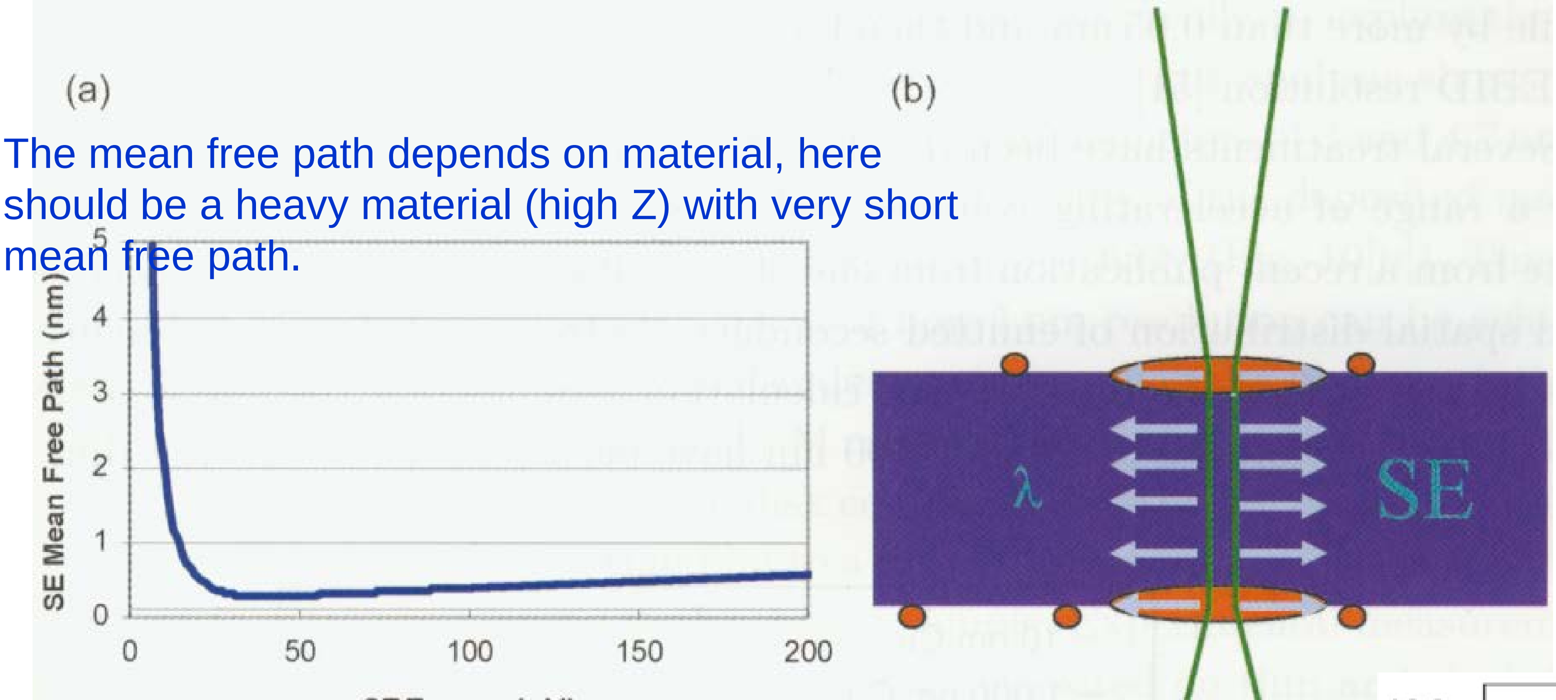


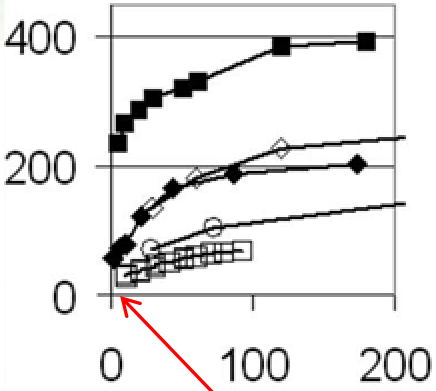
Fig. 12. The development of the width of an e-beam deposited structure.
(a) Experimental results. Inset shows the width development for short times.
(b) Result from a Monte Carlo simulation.

Vertical growth is due mostly to direct dissociation by PEs.
Lateral growth is due mostly to SEs.
In principle, lateral growth should stop once $d_{deposit} \approx d_{beam} + 2\times$SE escape length.
But BSE can go far away and generate SE there, so diameter can go quite large after long time.

High resolution deposition



The mean free path depends on material, here should be a heavy material (high Z) with very short mean free path.



Stop here

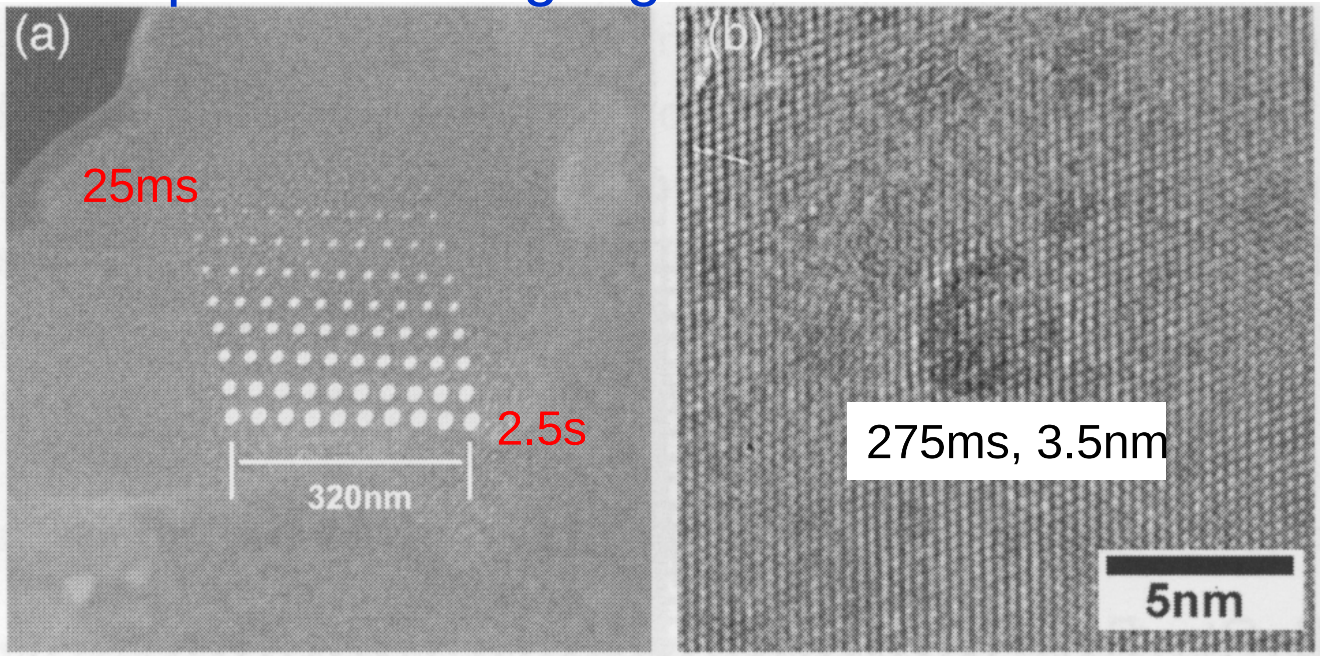
Strategy:

- Use high voltage STEM that has small beam spot size, and short deposit time (but then low aspect ratio).
- That is, stop deposition before significant lateral widening (by SE) occurs.

STEM: scanning transmission electron microscopy, beam <0.2nm.

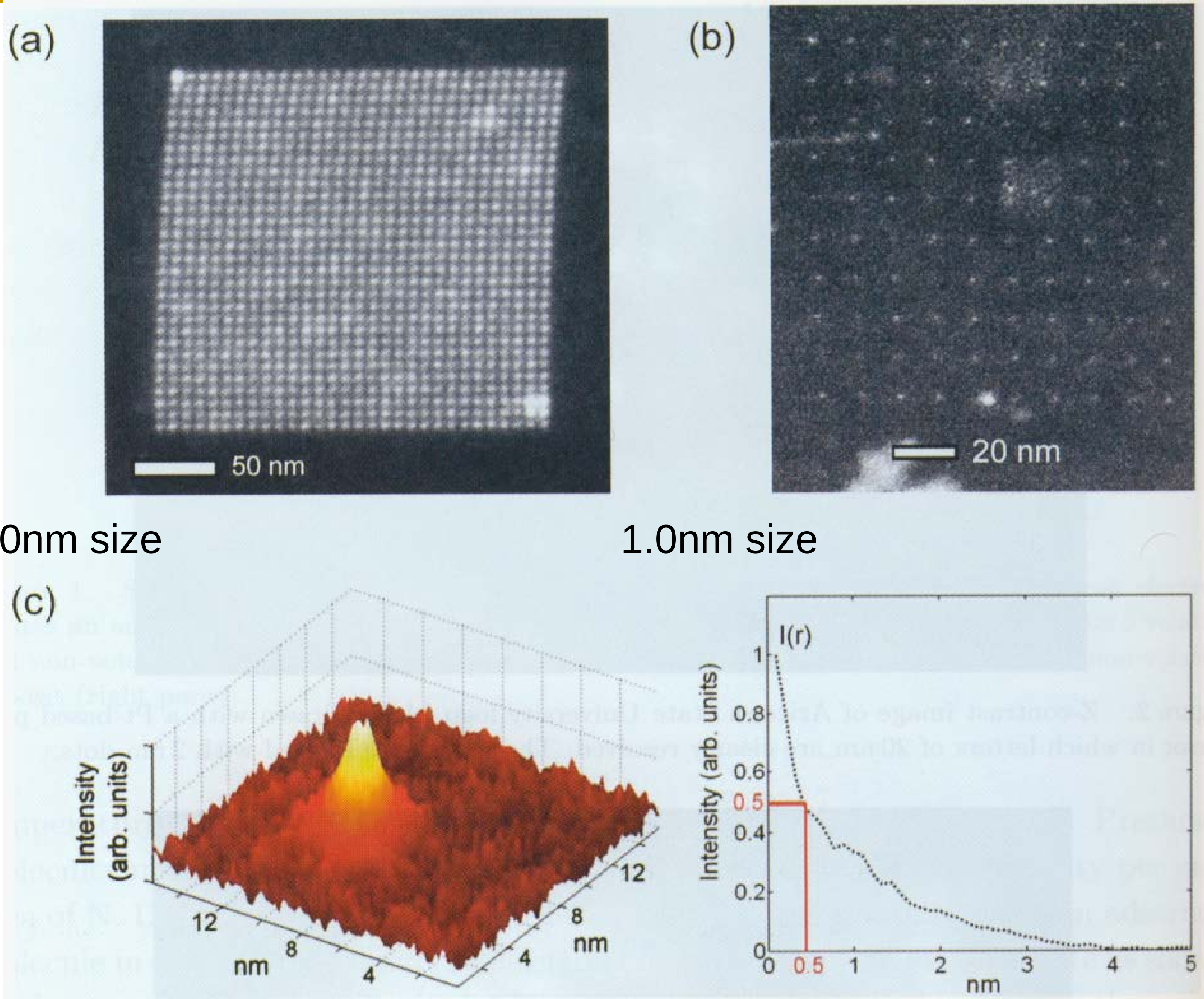
High resolution deposition examples

W deposition using high resolution STEM



Resolution is high, but aspect ratio is low, height/width order of 1.

High resolution deposition examples



4.0nm size

1.0nm size

W containing dots with $W(CO)_6$ precursor