Progress towards Low Vacuum Critical Dimension Metrology

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NIST FEI™

Outline

- **Introduction**
  - Critical Dimension Metrology (CD SEM)
  - Necessity for Modeling
- **Low Vacuum CD Metrology Approach**
  - Charge Control
  - Contamination Control
- **Principles of Low Vacuum SEM**
- **Analytical Modeling of Amplification and Noise Characteristics**
  - ESD (Environmental Secondary Electron Detector)
  - Helix (Magnetic Immersion Lens Detector)
- **Summary & Pending Work**

Critical Dimension (CD) Metrology

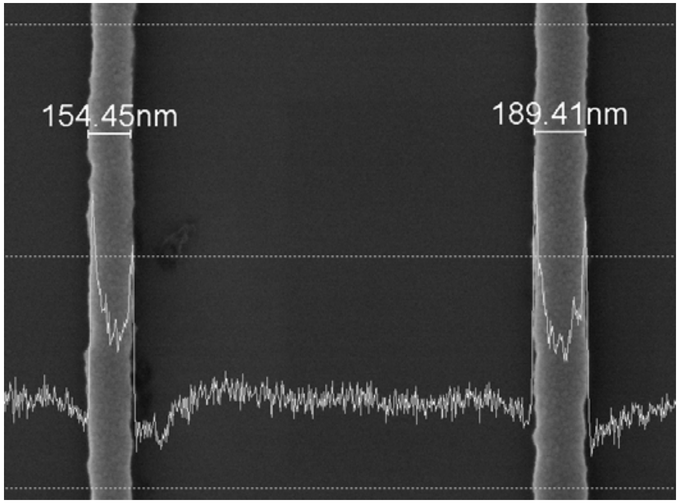
- **Scanning electron microscope methods are some of the most prevalent technologies for critical dimension (CD) measurement.**
  - High resolution imaging (spatial res. ~1nm, measurement res. ~1nm)
  - Acceptable throughput and speed (typically 1 wafer per ~5min, 17 points on wafer)
  - Site specific measurements
  - Well-established procedures for interpreting the results

- **CD's are rapidly approaching the limitations of conventional CD-SEM imposed by:**
  - Charging
  - Contamination
  - Specimen interaction volume
  - Secondary electron mean-free-path

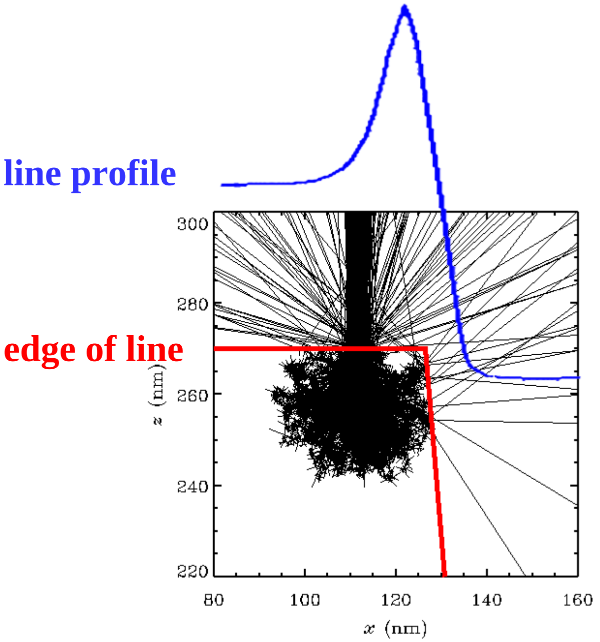
- **Low Vacuum SEM technology can address charging and contamination without sacrificing performance**

CD-SEM Measurement Process

- SEM information is distilled into an intensity profile
- The peaks indicate the position of the edges
- Simulation codes correlate peak position and shape with actual feature shape
  - Edge “blooming” effect

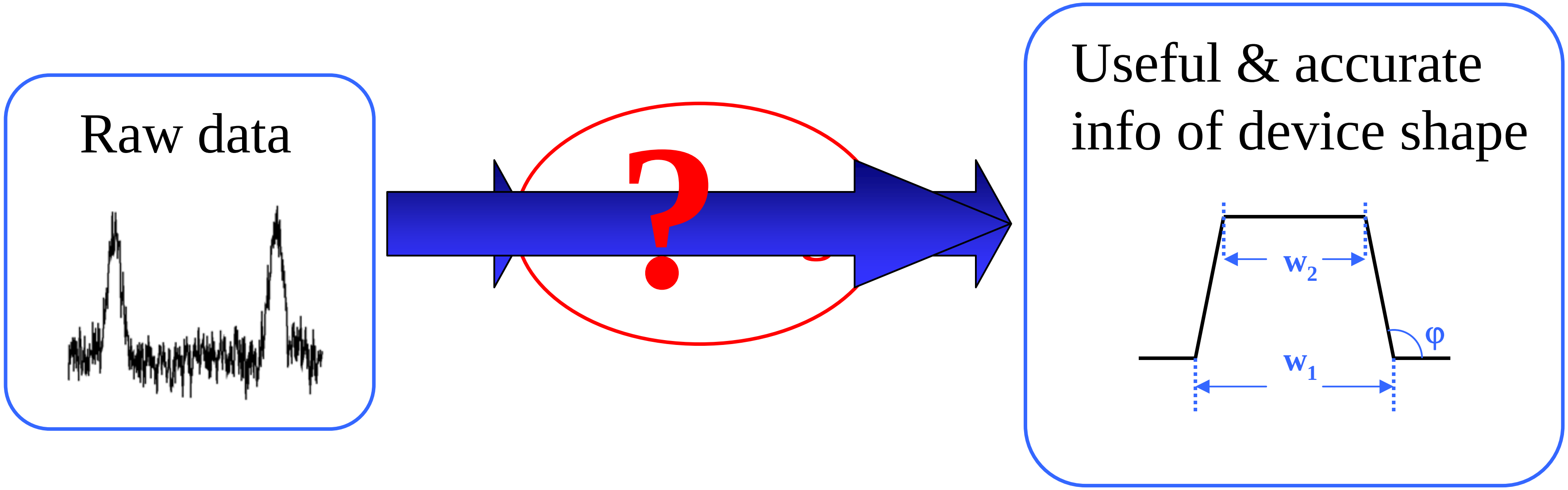


chrome-on-quartz photolithographic mask



MC simulation of electron trajectories near the edge of a line and corresponding line profile

Edge Assignment Problem



Raw data

?

Useful & accurate info of device shape

ITRS – Need for standardization of CD process,

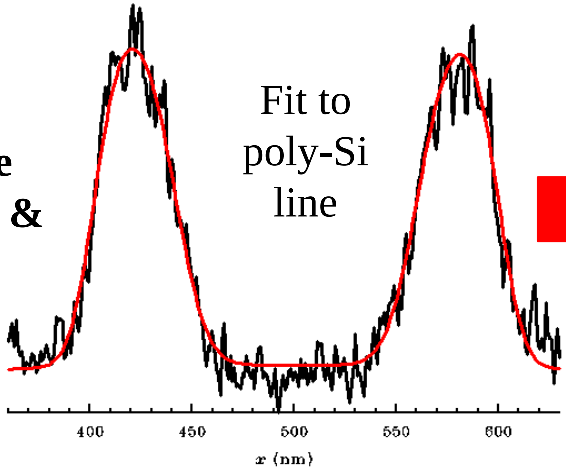
i.e. “robust conversion of massive quantities of raw data to information useful for enhancing the yield of the semiconductor manufacturing process”

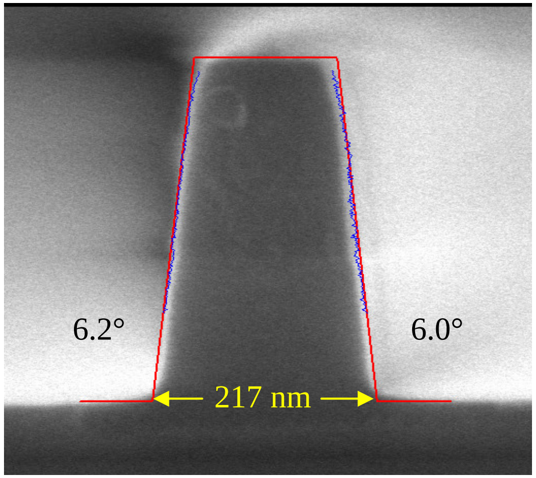
ITRS (International Technology Roadmap for Semiconductors) 2008 update / Metrology section

Modeling for Accuracy: MONSEL

- **Analytical descriptions** are implemented for **all physical processes**
  - **Electron beam/specimen interactions**
- **Instrumentation effects** are included
- Software that can reach, and if needed interpolate between a library of precomputed line profiles for model geometries
- Non-linear least squares algorithm solves for the particular set of parameters that produce the best least squares match between measured and calculated images

Top down image intensity profile &
Simulation fit





X-sectional image &
X-sectional fitted shape

J.R. Lowrey et al., Proc. SPIE 2196 (1994) 85

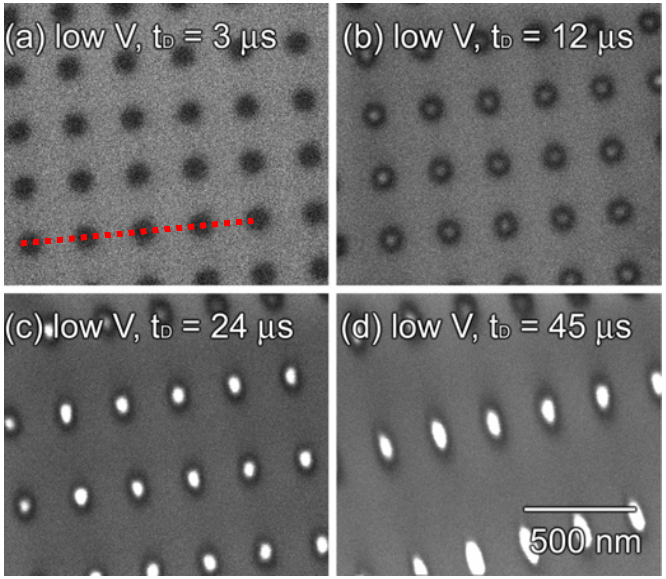
J.S. Villarrubia et al., Proc. SPIE 4689 (2000) 304

M.T. Postek et al., J. Vac. Sci. Technol. B 23 (2005) 3015

J.S. Villarrubia & Z.J. Ding, Proc. SPIE 7272 (2009)

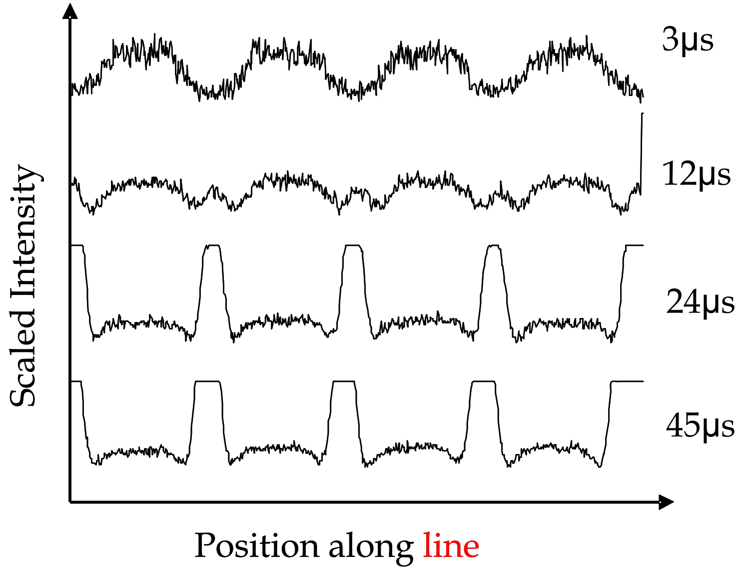
The Problem with Low Voltage CD SEM

- **CD measurement of non-conductors is challenging because charging effects depend strongly on imaging conditions and cause:**
  - Image distortion
  - Contrast inversion



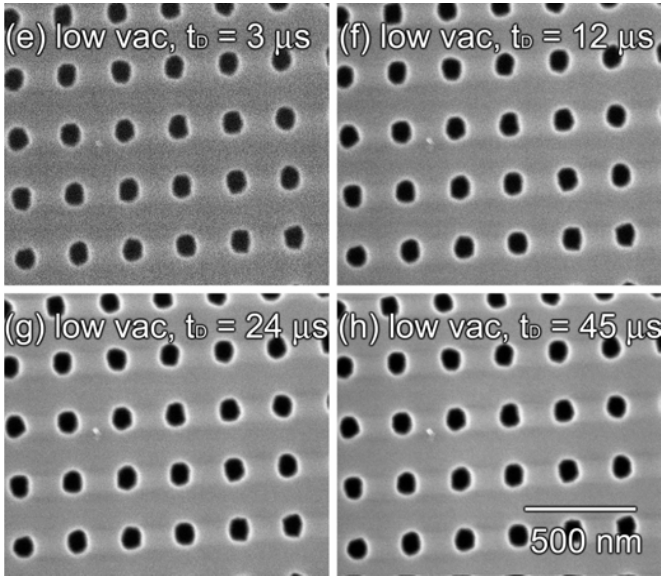
E_0=600eV
I_0=44pA

Si_3N_4 contact holes



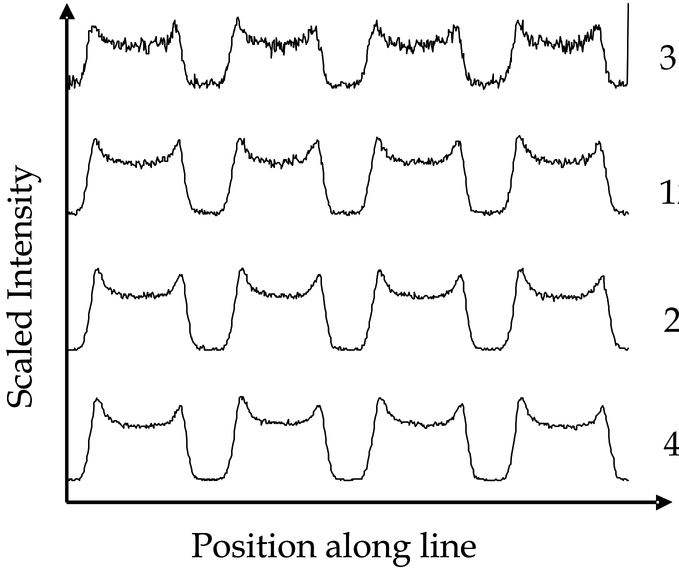
Low Vacuum CD-Related Advantages

- **Good charge control independent of scan rate**
- **Good SNR at even lower electron fluence**
- **Contrast is preserved**



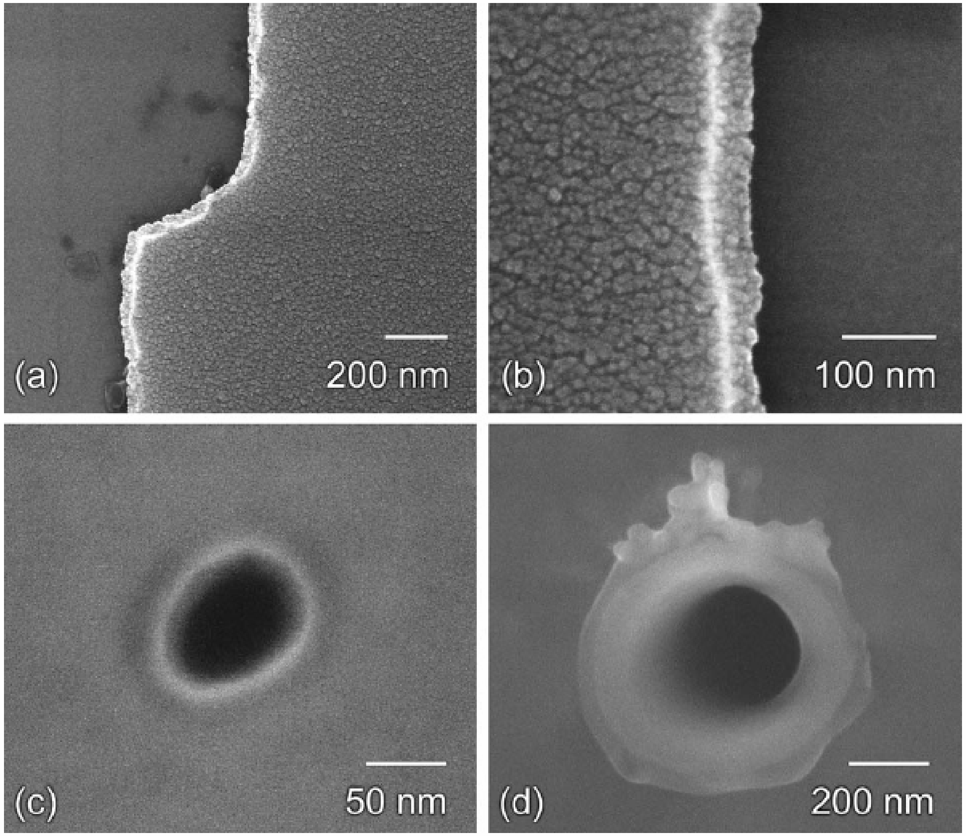
E_0=5keV
I_0=28pA

Si_3N_4 contact holes



Low Vacuum CD-Related Advantages

- **High resolution imaging with existing electron optics**



(a) & (b) chrome-on-quartz photolithographic mask

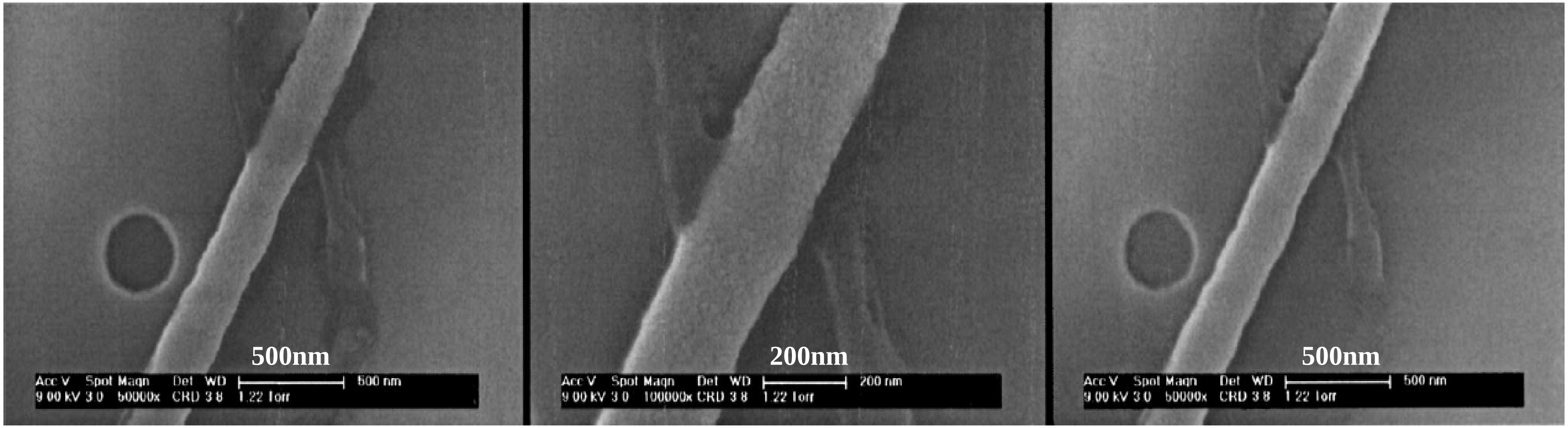
(c) contact hole in Si_3N_4

(d) electrostatic discharge pit in SiO_2

M. Toth et al., Appl. Phys. Lett. 88 (2006) 023105

Low Vacuum CD-Related Advantages

- **Hydrocarbon contamination is reduced**



3min e-beam irradiation

(a) no contamination square

(b) shrinkage of the residue

M.T. Postek et al., J. Microlith. Microfab. Microsyst. 3 (2004) 224

Low Vacuum CD Metrology – Overview

ITRS challenges for both ≤ & ≥ 22nm

- ✓ Surface charging stabilization
- ✓ High resolution imaging
- ✓ Contamination control

- ✗ Method for interpreting the results

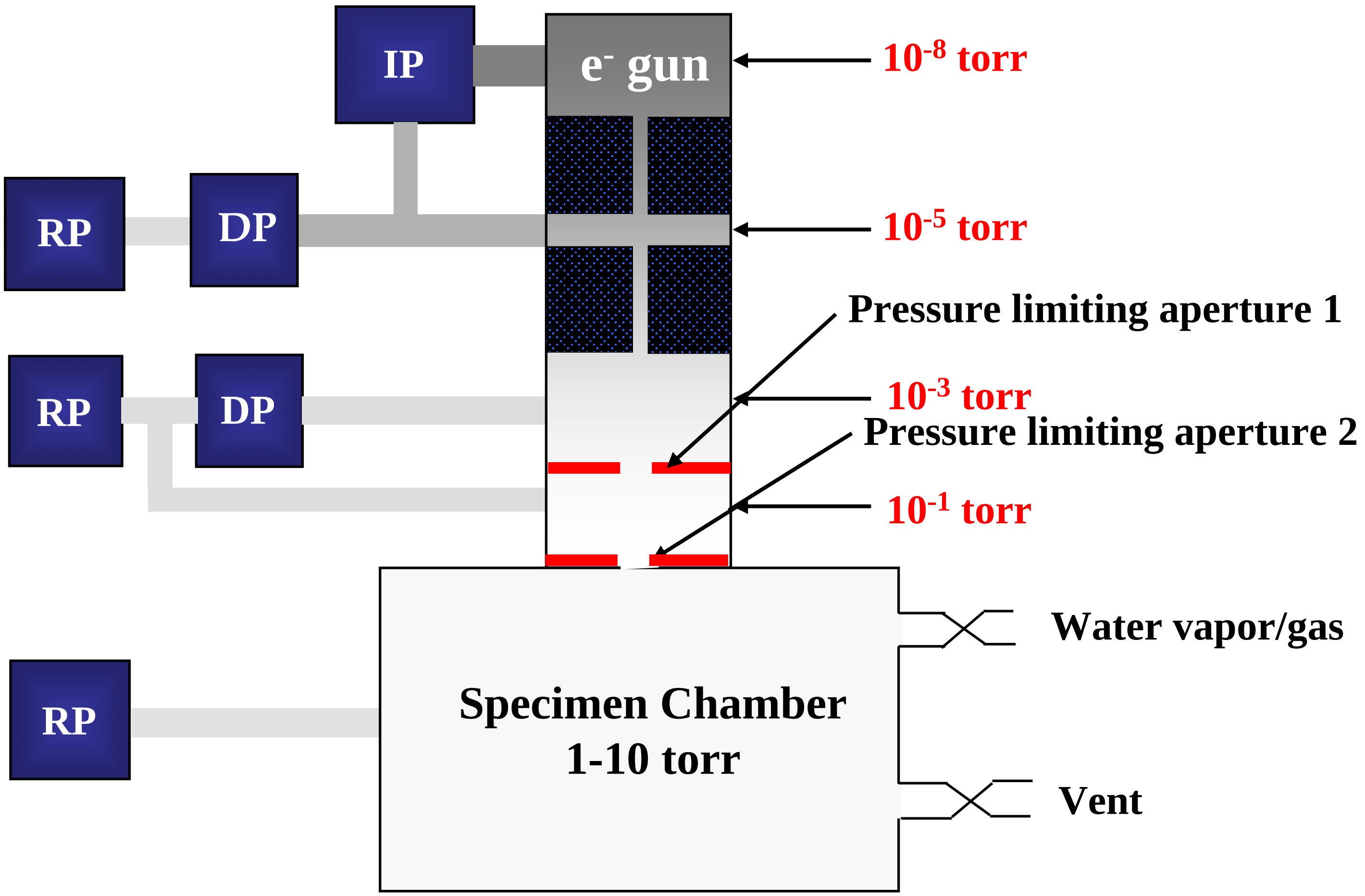
Critical Dimension (CD) Metrology

- Low Vacuum SEM technology can address charging and contamination without sacrificing performance

- How are optimal conditions determined for alleviating charging artifacts?
- How does the gas affect the incident beam?
- How does the gas affect the secondary electron emission?
- What are the sources of signal, background, and noise collected by the detector?

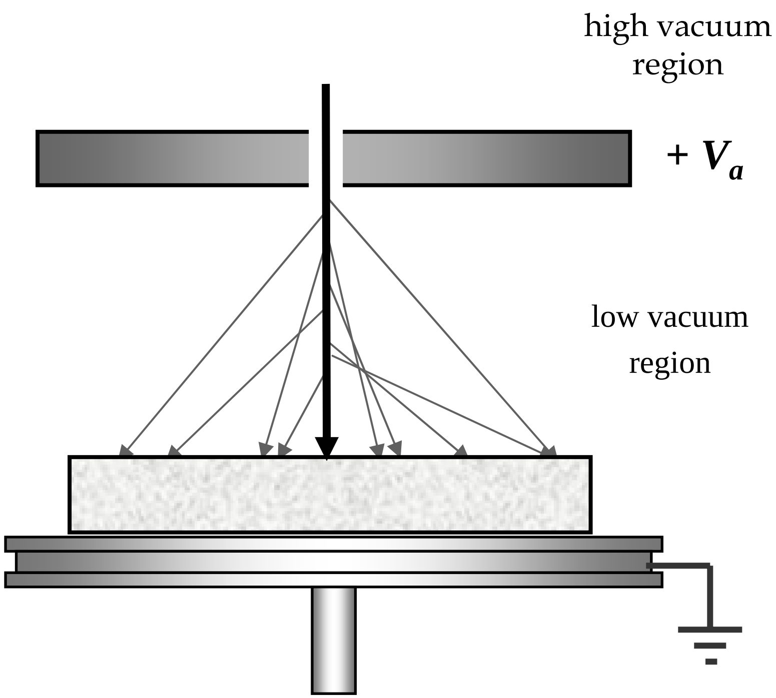
Low Vacuum SEM

The Low Vacuum SEM



Scattering of the Primary Beam

- Collisions of primary beam electrons with gas molecules result in a low current density “skirt” of scattered electrons surrounding the central beam
  - It can extend over several hundred micrometers
  - It does not degrade resolution
  - It contributes to the background



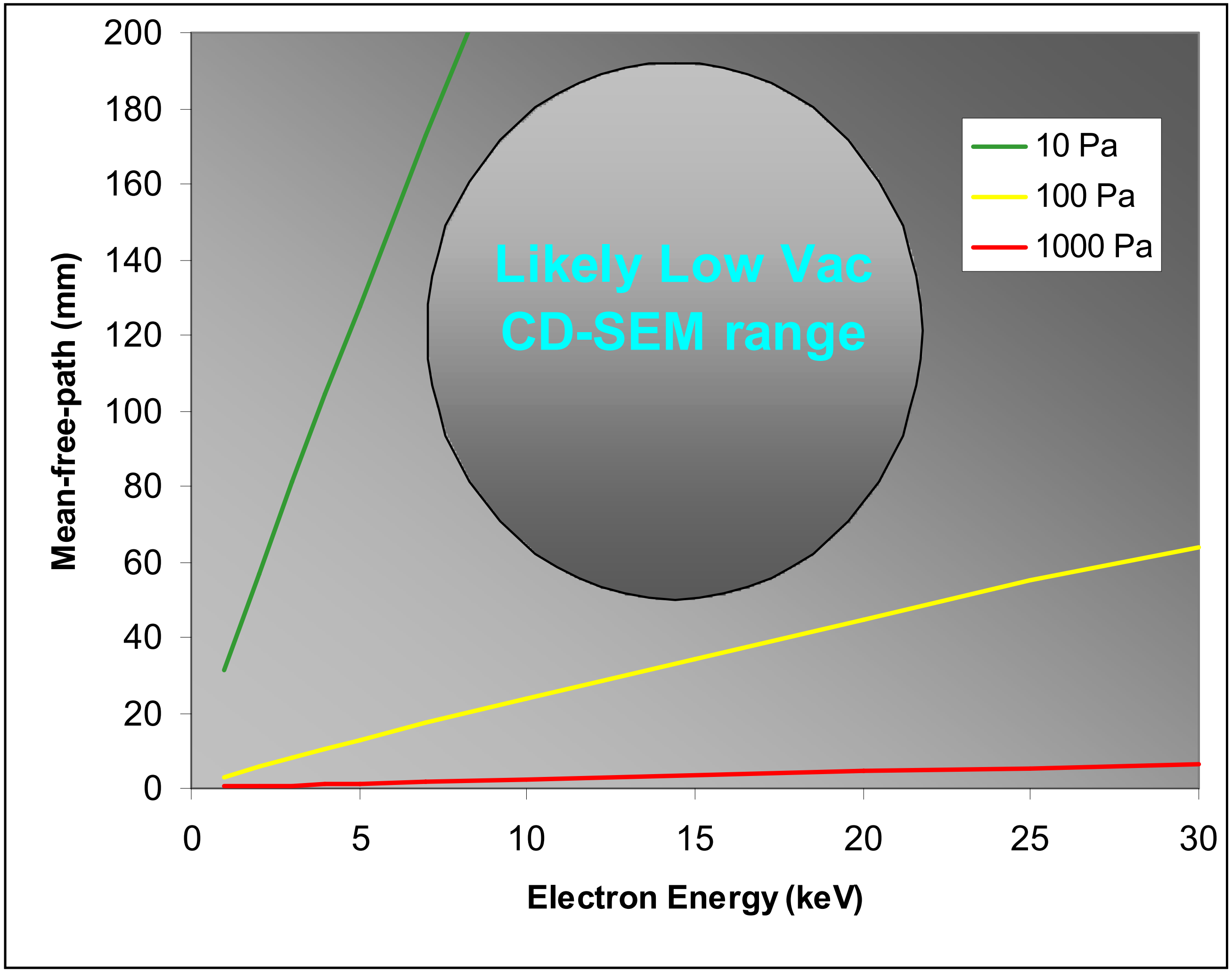
- The unscattered fraction of the beam is given by:

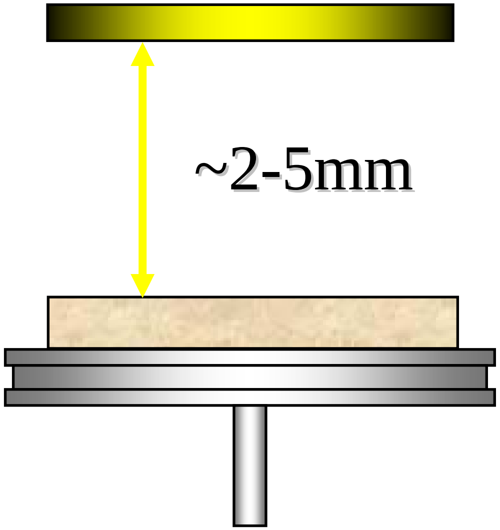
$$f = \exp\left(-\frac{Q(E)Pl}{RT}\right)$$

$Q(E)$: total scattering cross-section, P : gas pressure,
l : gas path length, R : gas constant, T : temperature

D.A. Moncrieff et al., J. Phys. D 12 (1979) 481
B.L. Thiel, Ultramicroscopy 99 (2004) 35

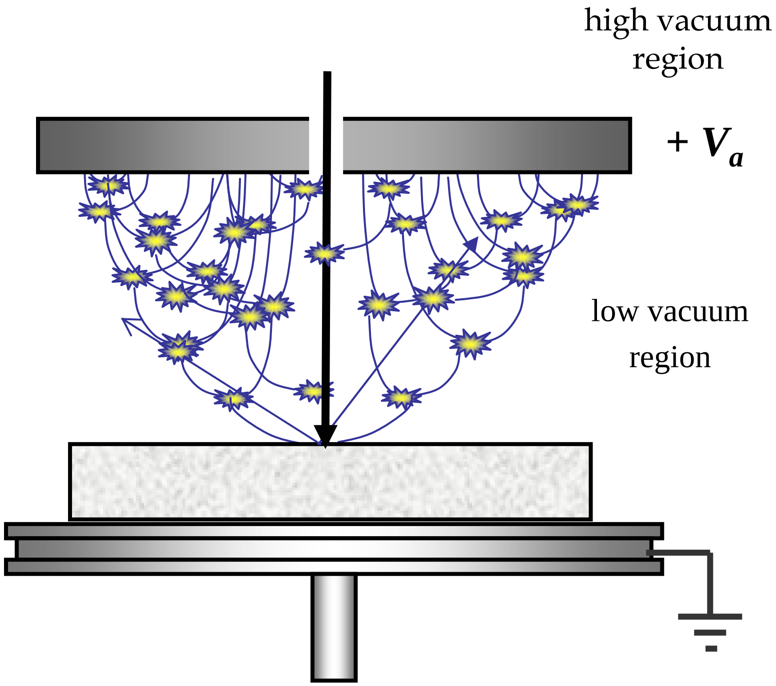
Mean free path of Electrons in H_2O Vapor





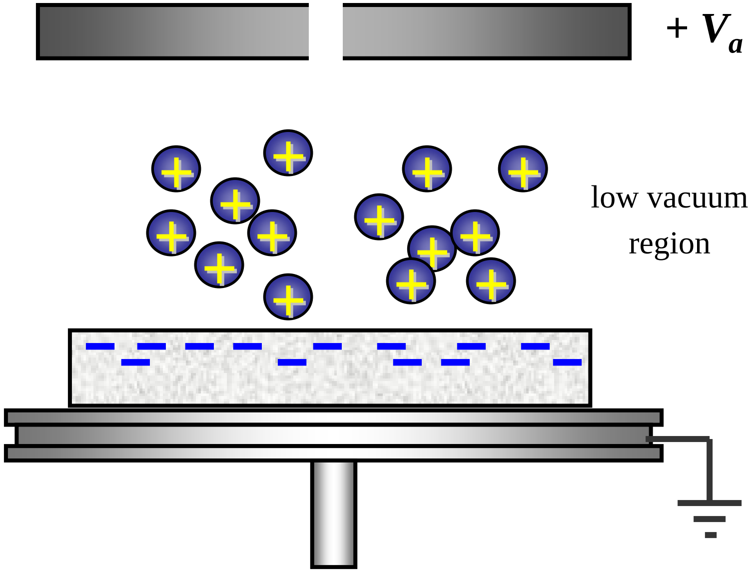
Gas Cascade Amplification

- The amplification of the emitted secondary electron (SE) signal takes place inside the chamber by ionizing collisions of the SEs with gas molecules
- A variety of electrodes and pole-pieces integrated into the final lens are used to create the electromagnetic field which drives the amplification cascade.
  - Signal
    - Normally amplified SEs (gain ~10^3)
  - Noise
    - SEs amplification is a stochastic process
  - Background
    - Inevitable multiplication of BSEs and PEs



Role of Ions

- Collisions of all emissions with gas molecules create positive gaseous ions
- Ions flow to regions of the specimen surface with a negative potential
- Ions recombine at surface, removing excess electronic charge



Low Vacuum SEM: Challenges

- **Operating parameter space is much larger to optimize**
  - **High Vacuum**
    - Beam energy
    - Beam current
    - Dwell time
    - Working distance
  - **Low Vacuum**
    - Beam energy
    - Beam current
    - Dwell time
    - Working distance
    - Gas-path-lengh
    - Cascade distance
    - Gas type
    - Gas pressure
    - Detector bias
- **Charge control is a strong function of operating conditions**
- **Signal, background, and noise production are strong functions of operating conditions**
  - SE signal amplification via gas ionization cascade
  - Background due to elastic-scattering of the primary beam
  - Background due to inelastic high-energy electron scattering
  - Excess noise due to stochastic nature of cascade amplification

Cascade Amplification in a Constant Field

ESD

- **Allows study of fundamental electron-gas interactions in a simple geometry**
  - Uniform electric field
  - Ionization efficiency largely independent of position in cascade

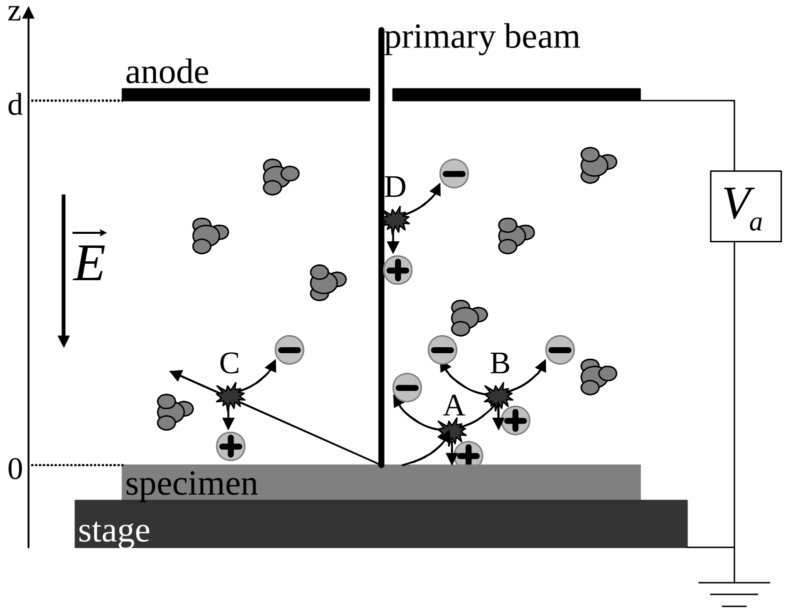
$$\alpha = AP\exp\left(-\frac{BPd}{V_a}\right)$$

A,B : gas-specific parameters

P : pressure

d : cascade distance

V_a : detector bias



A: ionizing events caused by secondary electrons (SEs) emitted from the specimen;

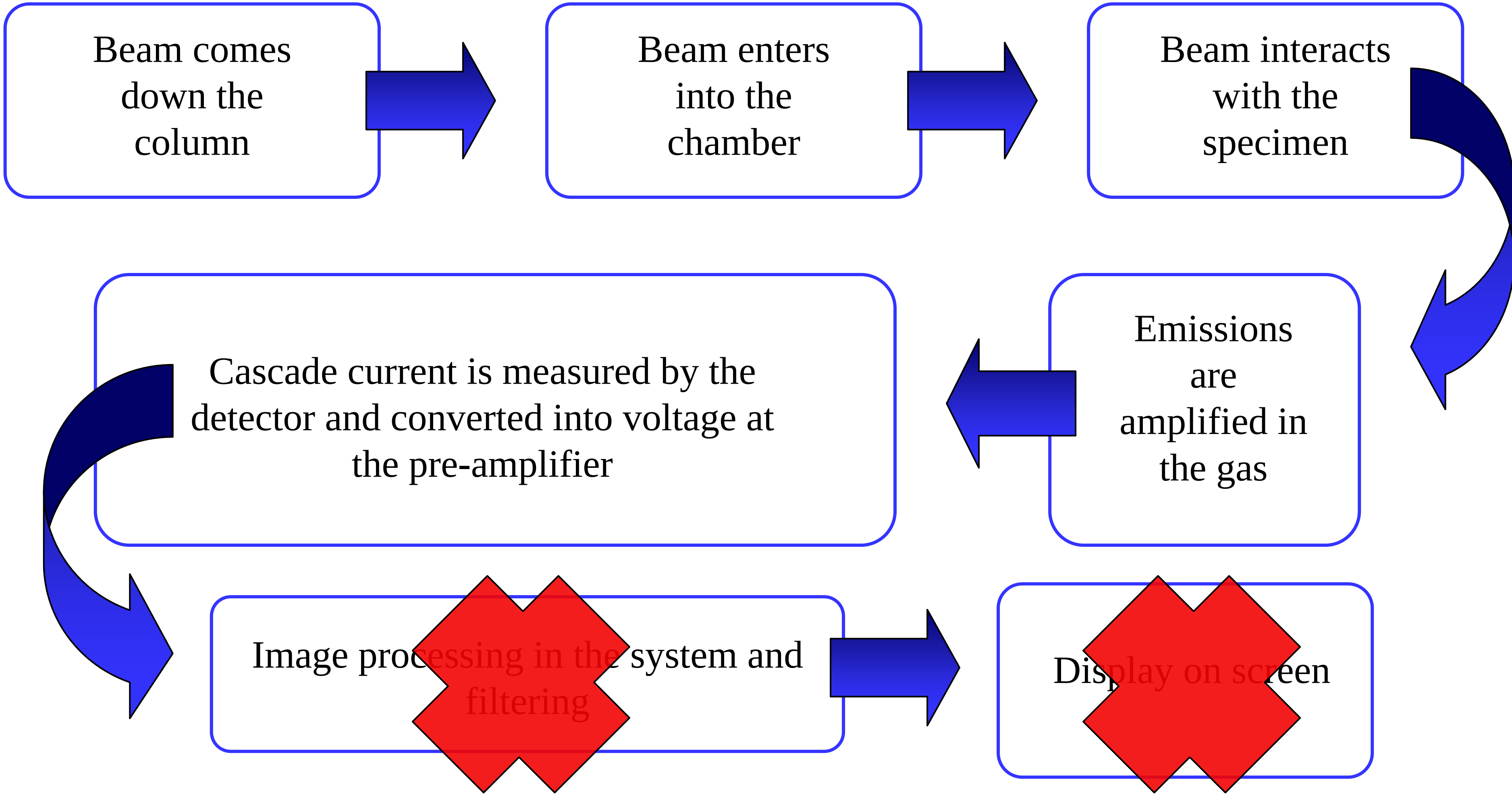
B: multiplication process;

C: ionizing events caused by backscattered electrons (BSEs);

D: corresponding effect caused by primary electrons (PEs).

A. von Engel, *Ionized gases* (Clarendon Press, Oxford, 1955)

Flow Chart of the Signal Chain



Beam comes down the column

Beam enters into the chamber

Beam interacts with the specimen

Emissions are amplified in the gas

Cascade current is measured by the detector and converted into voltage at the pre-amplifier

Image processing in the system and filtering

Display on screen

Amplified SE Signal

- The secondary electron cascade current I_s arriving at the detector can be described by the following equation:

$$I_s = I_o \delta \; f \exp(\alpha d)$$

I_o : primary electron beam current
δ : secondary electron yield
α : gas ionization efficiency
d : cascade distance
f : fraction of primary electrons that do not scatter into the skirt

- However, this needs to be modified in order to include the total measured signal in our experimental set-up
  - Addition of all SEs (included those generated by the skirt, BSEs, & PEs

$$I = \left(\delta \exp(\alpha d) + \frac{\eta S_{BSE} P}{\alpha} \exp(\alpha d - 1) + \frac{S_{PE} P}{\alpha} \exp(\alpha d - 1) \right) I_o$$

D.A. Moncrieff et al., J. Phys. D 11 (1978) 2315

D.A. Moncrieff et al., J. Phys. D 12 (1979) 481

Sources of Noise

- **Beam or shot noise:** Arising from Poisson distribution of emission of e^-.

$$N_{BE} = \sqrt{2eI_o b}$$

e : electron charge
I_o: primary beam current
b : signal bandwidth

- **Gas cascade noise:** Arising from the formation of plasma in the chamber.
  - Contribution to noise from:
    - Secondary Electrons (SEs)
    - Primary Electrons (PEs)
    - Backscattered Electrons (BSEs)

- **Amplifier or Johnson's noise:** Arising from thermal and electronic noise in the detection system.

$$N_{AMP} = \sqrt{4kTRb}$$

k : Boltzmann's constant
T : temperature
R : resistor

W. Shockley and J. R. Pierce, Proc. IRE 26 (1938) 321

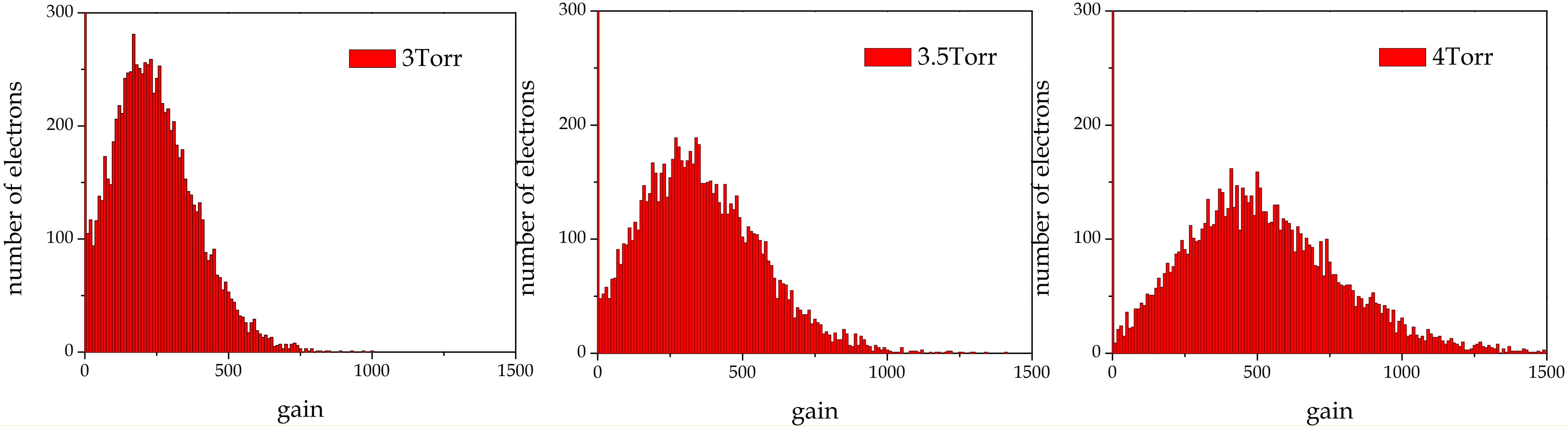
J. Johnson, Phys. Rev. 32 (1928) 97

Cascade Noise: Model

- The physical process of ionization of the gas in the presence of an electric field is similar to that of the production of e^- - h^+ pairs in an avalanche photodiode
- The contribution to noise from the cascade is:

$$N = \sqrt{M^2 F_e}$$

M : amplification factor (gain)
F_e : excess noise factor (gain uncertainty)



R.J. McIntyre, IEEE Trans. El. Dev. ED 13 (1966) 164
K. Tillotson, "Excess noise factor of the gas ionization cascade calculated by statistical analysis of Monte Carlo gain distributions", in preparation
R.J. McIntyre, IEEE Trans. El. Dev. 46 (1999) 1623
Cascade Monte Carlo Software

Cascade Noise: Model

- The physical process of ionization of the gas in the presence of an electric field is similar to that of the production of e^- - h^+ pairs in an avalanche photodiode
- The contribution to noise from the cascade is:

$$N = \sqrt{M^2 F_e}$$

M : amplification factor (gain)
F_e : excess noise factor (gain uncertainty)

- Application of the model for single carrier initiated/single carrier multiplication conditions (the lowest noise case for diodes) gives:

$$F_e = 2 - \frac{1}{M}$$

- Therefore the multiplication noise can be described by the equation:

$$N = \sqrt{M\left(2M - 1\right)}$$

R.J. McIntyre, IEEE Trans. El. Dev. ED 13 (1966) 164

R.J. McIntyre, IEEE Trans. El. Dev. 46 (1999) 1623

Cascade Contributions to Noise

- **Secondary electrons**

$$N_{SE} = \sqrt{2eI_o b\left(\delta(\delta+1)\right)\exp(\alpha d)\left(2\exp(\alpha d)-1\right)}$$

- **Primary electrons**

$$N_{PE} = \sqrt{2eI_o b S_{PE} Pl\left(\frac{\exp(\alpha d)-1}{\alpha d}\right)\left(2\frac{\exp(\alpha d)-1}{\alpha d}-1\right)}$$

- **Backscattered electrons**

$$N_{BSE} = \sqrt{2eI_o b\eta S_{BSE} Pl\left(\frac{\exp(\alpha d)-1}{\alpha d}\right)\left(2\frac{\exp(\alpha d)-1}{\alpha d}-1\right)}$$

I_o : primary beam current

e : electron charge

b : bandwidth

α: gas ionization efficiency

δ: SE yield

S_{PE} & S_{BSE}: PEs & BSEs ionization efficiency

P : pressure

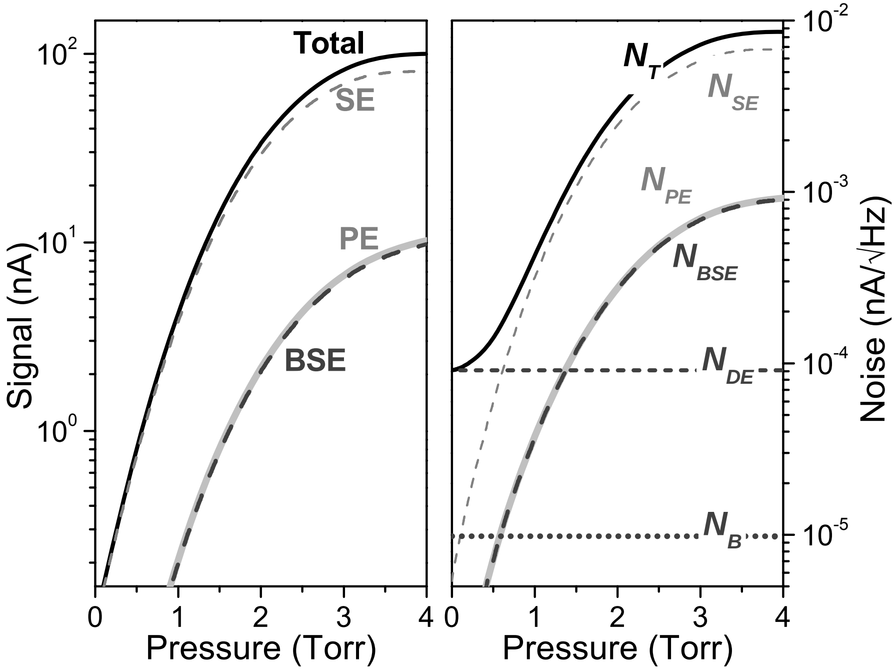
l : gas path length

d : cascade distance

η : BSE yield

V. Tileli et al., "Noise characteristics of the gas ionization cascade used in low vacuum scanning electron microscopy", submitted to *J. App. Phys.*

Signal and Noise Contributions

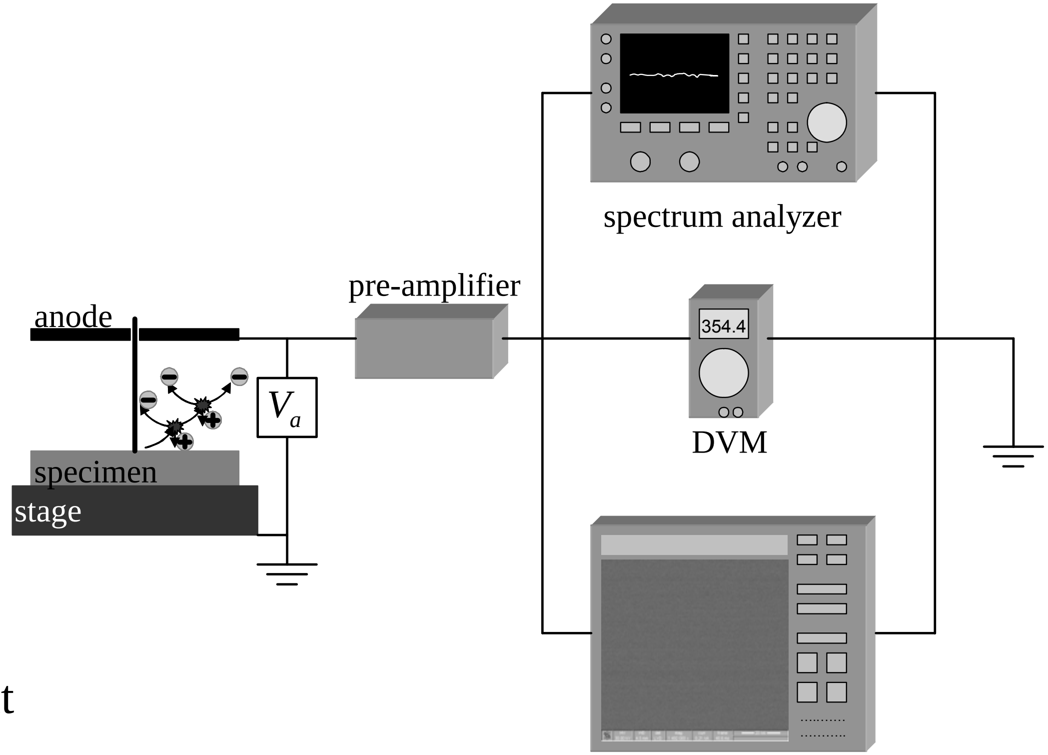


- Total signal driven by the SE contribution
- Total noise dominated by:
  - Amplifier noise at low pressures
  - SE cascade component at high pressures

operating conditions: Eo=15keV, Io=300pA, Va=400V, d=5mm

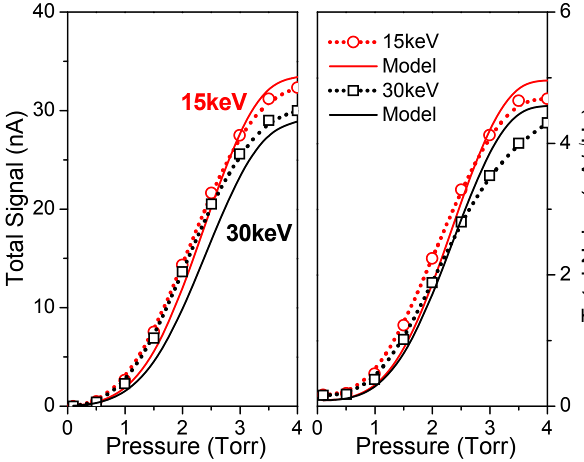
Experimental Set-up

- **SEM data**
  - FEI Nova NanoSEM
- **Signal data**
  - Digital volt meter (DVM) connected to the output of the pre-amplifier
- **Noise data**
  - Agilent E4401B Spectrum Analyzer connected to the output of the pre-amplifier
    - Noise marker function

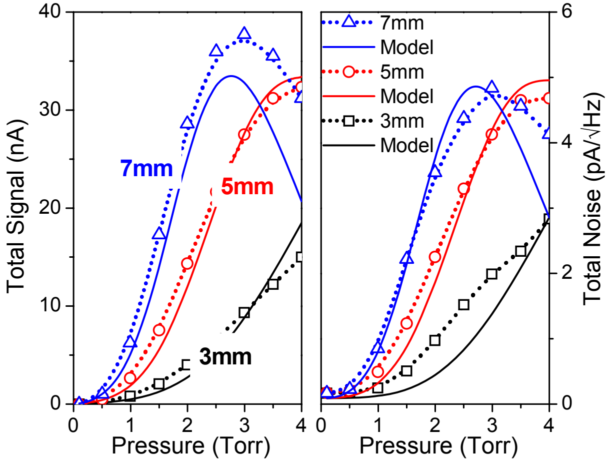


Signal and Noise

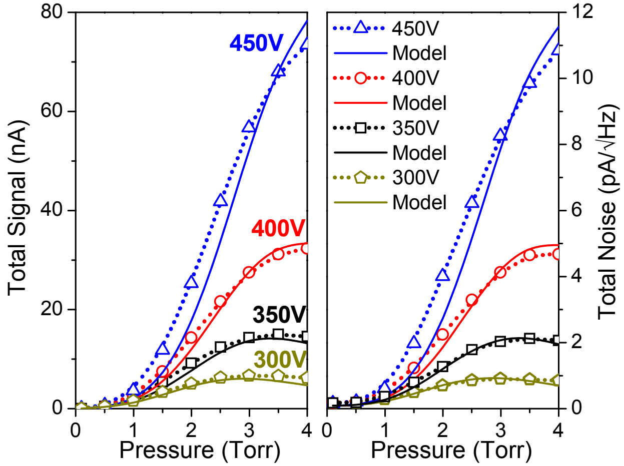
beam energy E_o



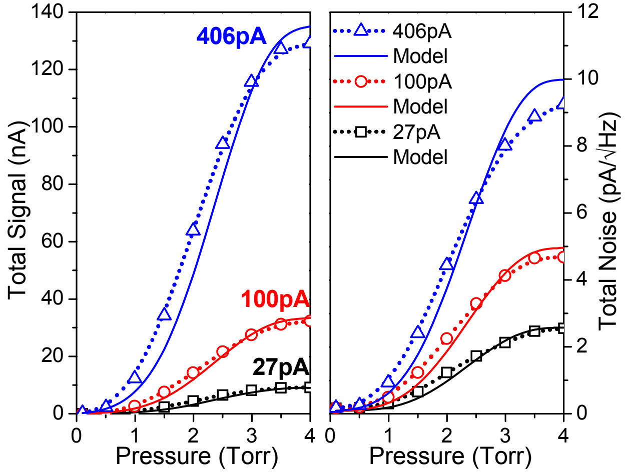
anode/specimen separation d



detector bias V_a



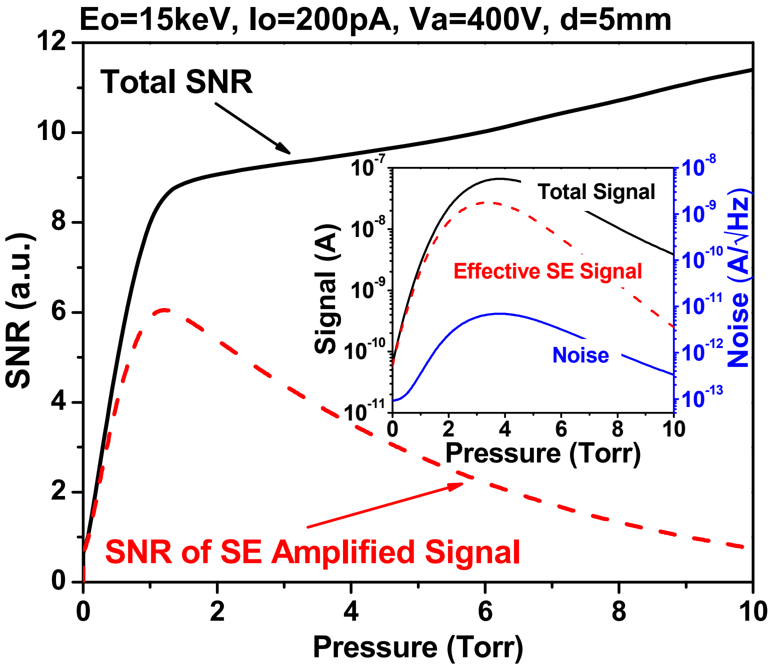
beam current I_o

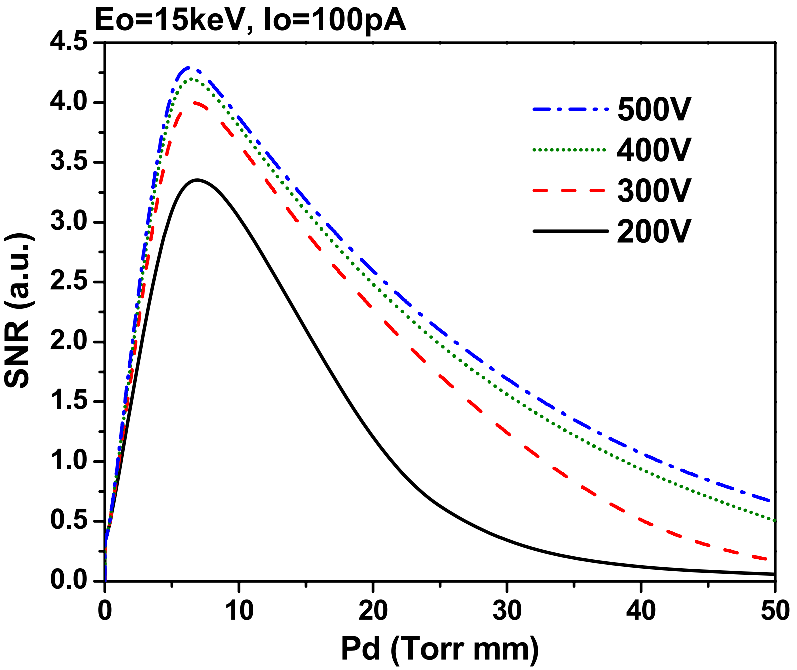


- Total signal increases as the primary beam energy is lowered
- The pressure at which maximum gain occurs is proportional to the electric field strength
- Maximum gain is an exponential function of the anode bias
- Total signal is proportional to the incident current

V. Tileli et al., "Noise characteristics of the gas ionization cascade used in low vacuum scanning electron microscopy", submitted to *J. App. Phys.*

Signal-to-Noise Ratio (SNR)



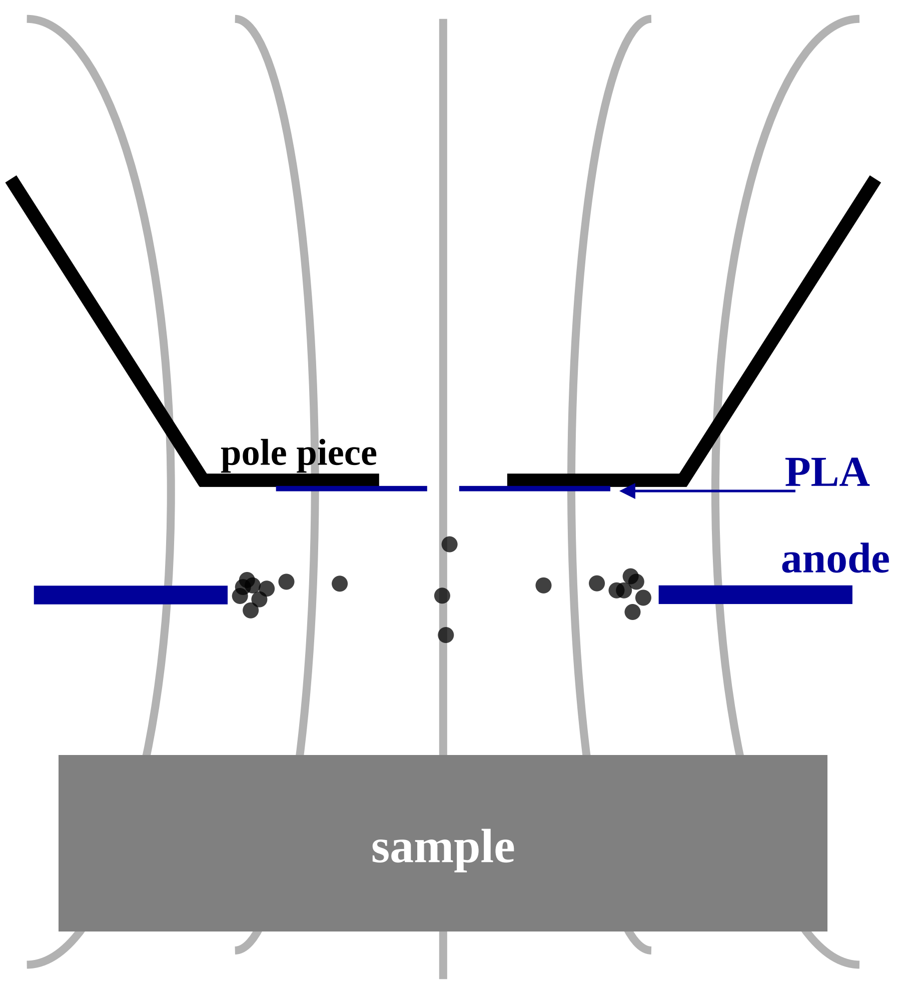


- Total cascade current reaching the detector contains a significant background component
- Optimization through the master curve approach

V. Tileli et al., "Noise characteristics of the gas ionization cascade used in low vacuum scanning electron microscopy", submitted to *J. App. Phys.*

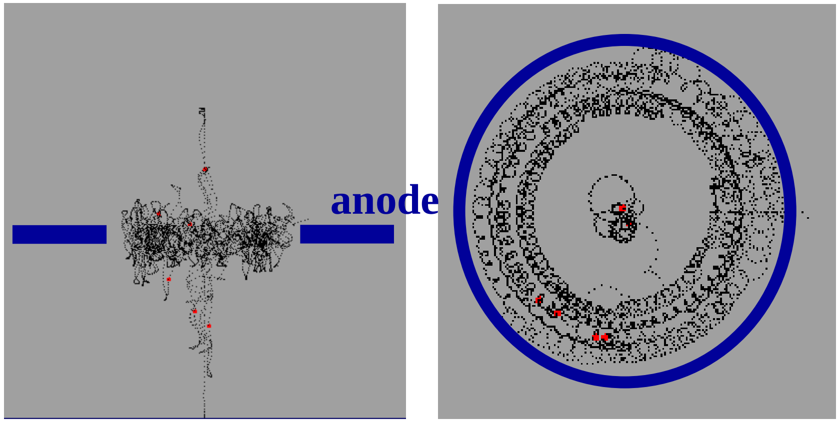
Low Vacuum Immersion Lens Detector – Helix™

Helix™



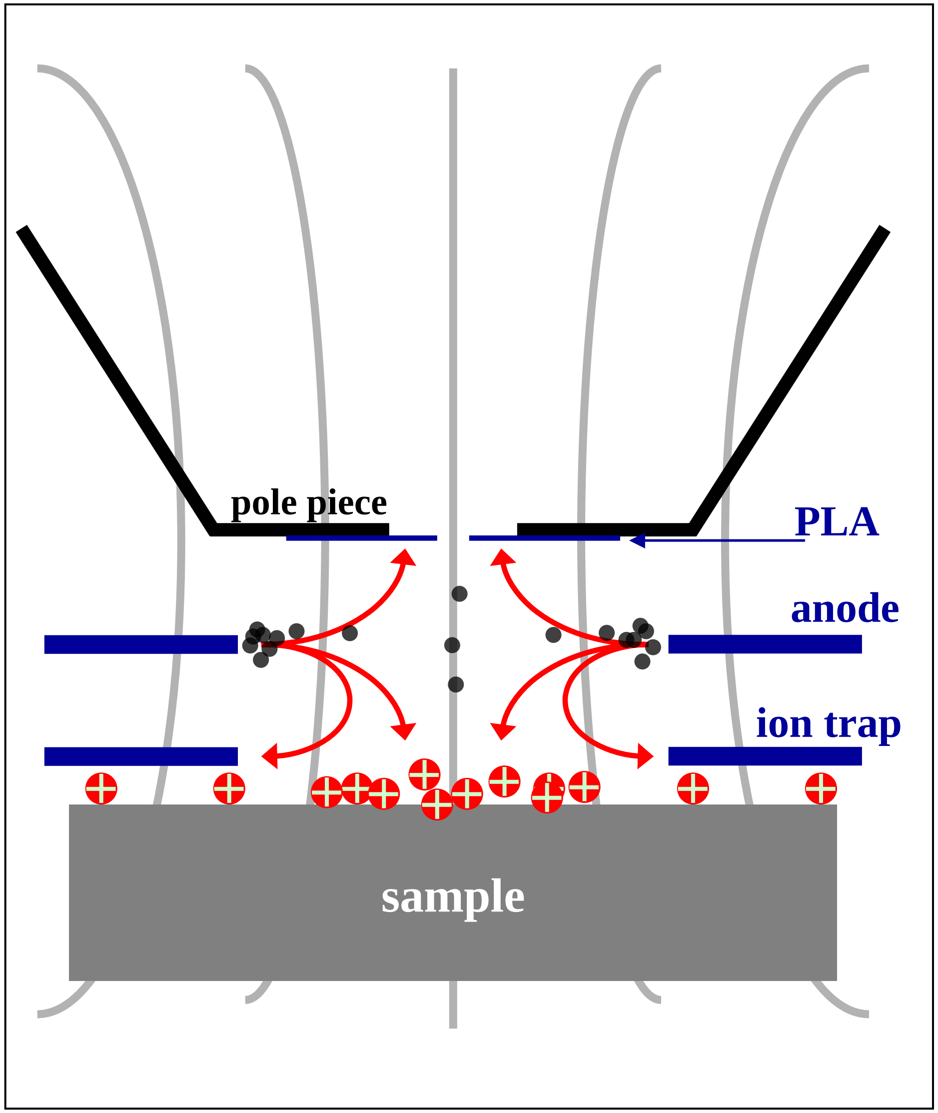
- SEs are attracted by an electric field, confined by a magnetic field
- Most amplification takes place along the anode periphery

Monte Carlo simulation of a single SE trajectory inside the detector



B.L. Thiel et al., Rev. Sci. Instr. 77 (2006) 033705
M. Toth et al., Appl. Phys. Lett. 88 (2006) 023105

Helix™

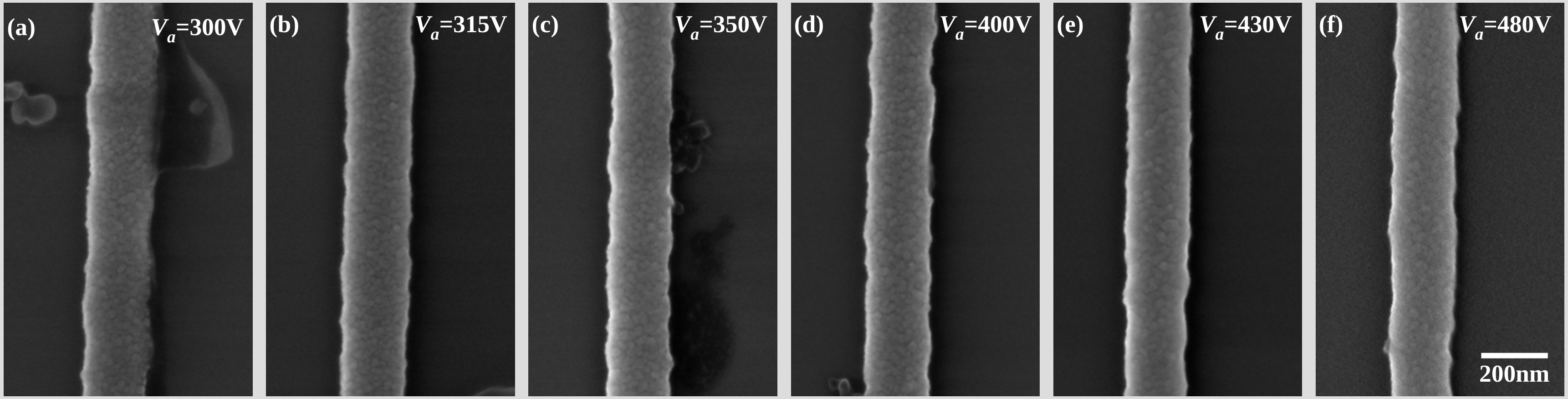


Ions

- Generated along the anode and the beam axis
- ~ ½ drift up to the PLA, and ½ down to the sample
- Excess ions charge up the sample surface, reduce the detector field & give rise to imaging artifacts (gain 10^3)
- Ion trap helps in self-regulation of ion current reaching the sample

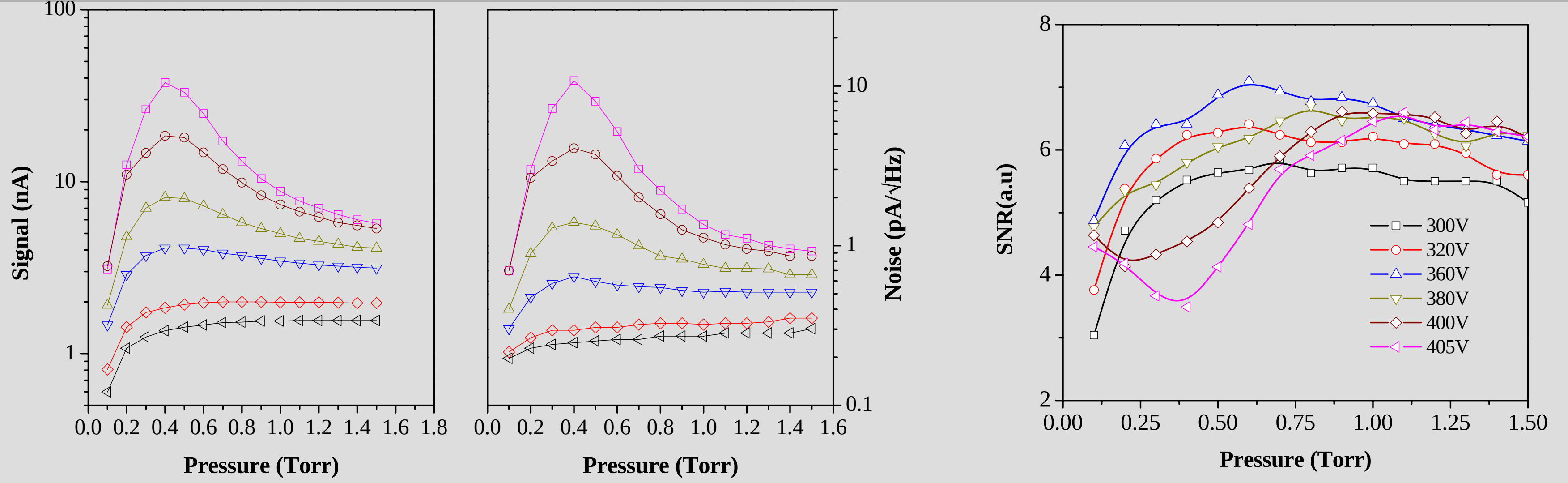
B.L. Thiel et al., Rev. Sci. Instr. 77 (2006) 033705
M. Toth et al., Appl. Phys. Lett. 88 (2006) 023105

Helix™ – Optimizing Imaging Conditions



Operating parameters: Eo=10kV, WD=5mm, Io=~100pA, Bf=200mT

Operating parameters: Eo=5kV, WD=4mm, Io=~100pA, Bf=200mT, Pt



Good charge control and SNR achievable but not intuitive

Summary & Pending Work

- Low Vacuum SEM can be a viable approach for high resolution CD Metrology if appropriate modeling of the instrumental effects is developed

- Charge control and contamination reduction have been demonstrated

- Analytical signal and noise performance for the constant field cascade were modeled successfully

Remaining Work

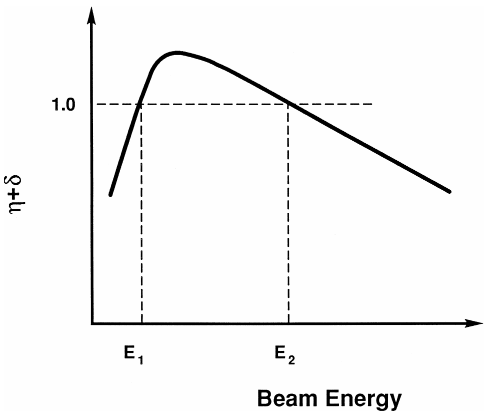
- Identification of the optimal gas composition for CD measurements
- Generalize analytical expressions for the gain and noise processes for complex detector configurations
- Develop analytical expressions for non-linear cascade processes
  - Breakdown (secondary ionization effects)
  - Scavenging (recombination of SE’s with ions)
- Establish the limits of charge control under low vacuum conditions
- Evaluate the model for incorporation in the CD simulation code MONSEL for the realization of Low Vacuum Critical Dimension Metrology

Back-up slides

Low Voltage vs. Low Vacuum

Useful SEM imaging of dielectrics, i.e. no charging artifacts, is possible by:

Low voltage

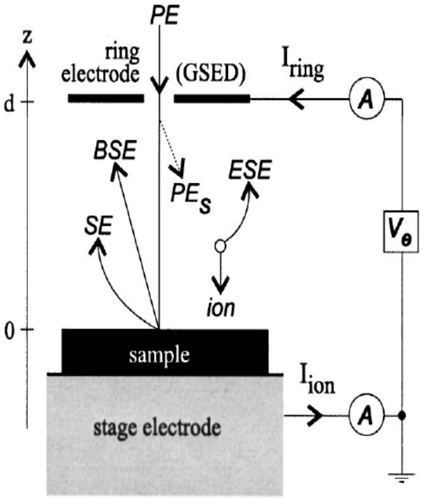


Charging is stabilized by fine-tuning of the electron beam energy to a critical value E_2

But E_2:

- Is specimen dependent
- Can vary within the imaged area
- Is a function of electron fluence

Low vacuum



Charging is stabilized by a weakly ionized gas inside the specimen chamber

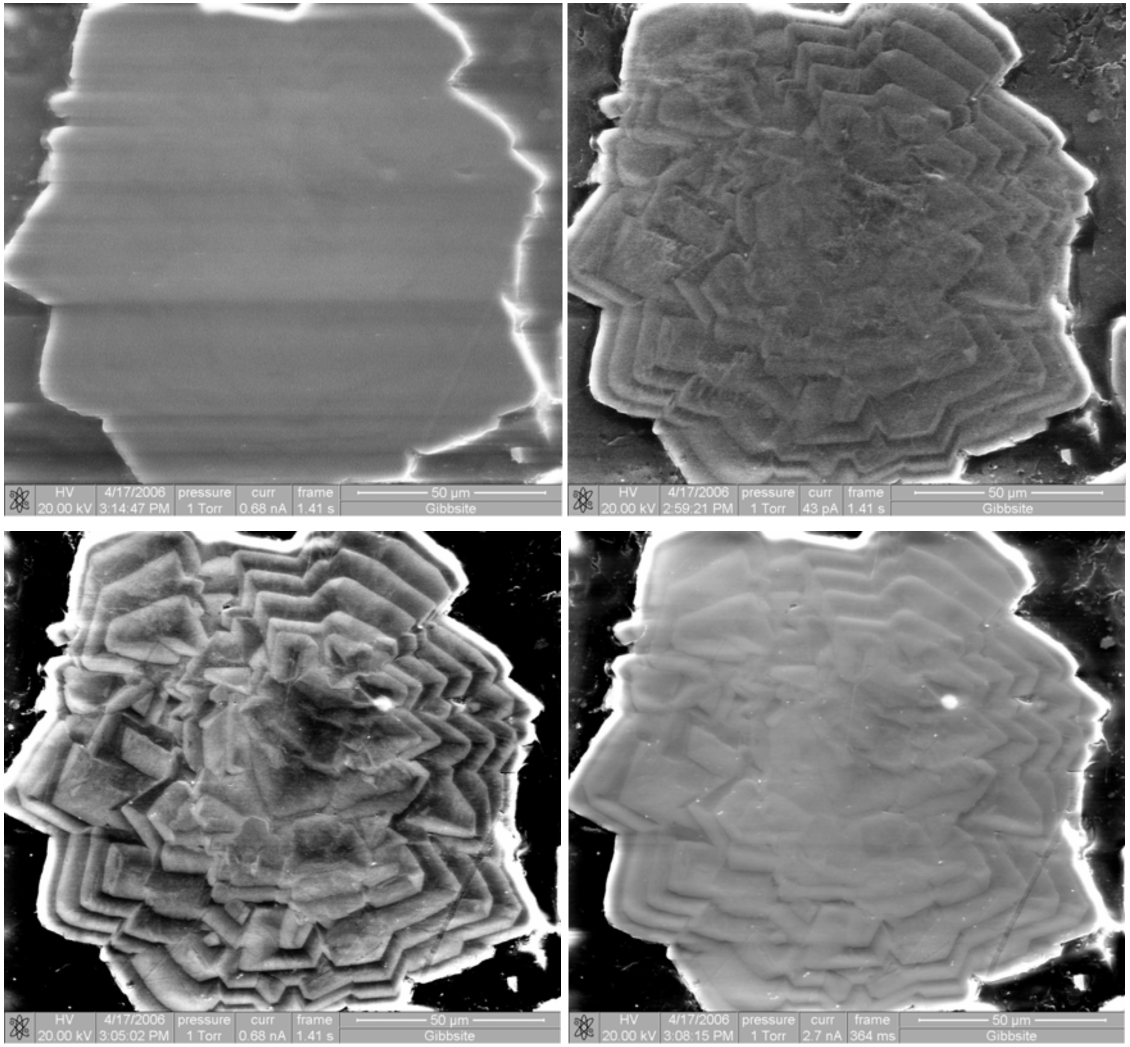
Effective because it does not rely on:

- Landing energy modulation
- SE recollection by the sample

Both suppress imaging artifacts but neither actually eliminates charging

Advantages of Low Vacuum SEM

- It stabilizes the surface potential
- It removes restriction on beam energy allowing it to be chosen on the bases of different criteria
- It eliminates image distortion
  - Image fidelity on metrology does not depend on imaging conditions
- It allows true SE imaging
  - Low voltage gives a signal complimentary to the backscattered
- It is potentially useful for acquiring information on buried structures
  - SE contrast reflects the local dielectric properties



Summing the Noise

Uncorrelated events add up in quadrature, correlated sum linearly

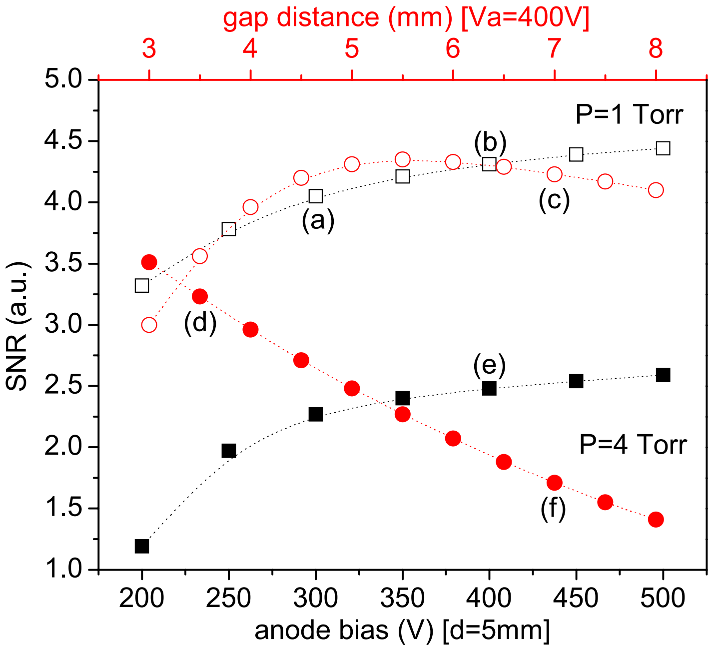
- All processes that take place in the cascade are correlated events
  - After ionization collisions, PEs and BSEs generate SE cascade

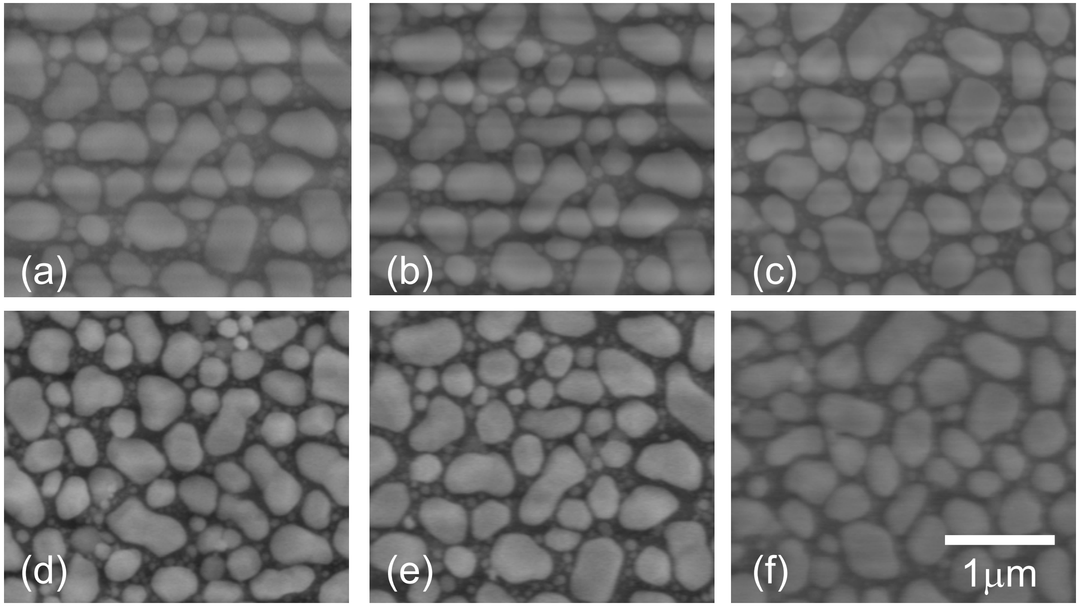
- Amplifier noise is independent of cascade processes

Therefore:

$$N_T = \sqrt{\left(N_{SE} + N_{BSE} + N_{PE}\right)^2 + N_{AMP}{}^2}$$

Image Analysis – ESD

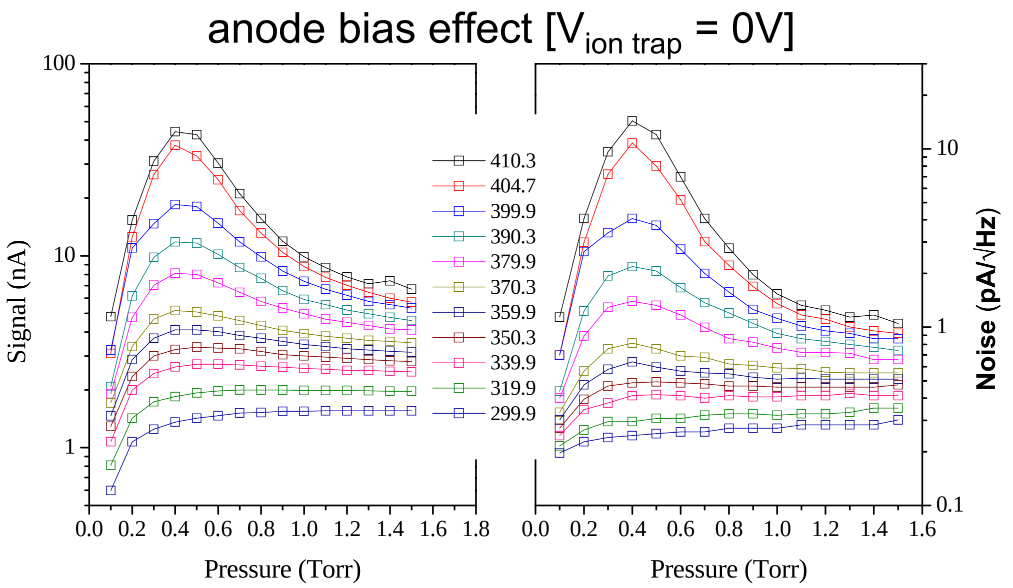


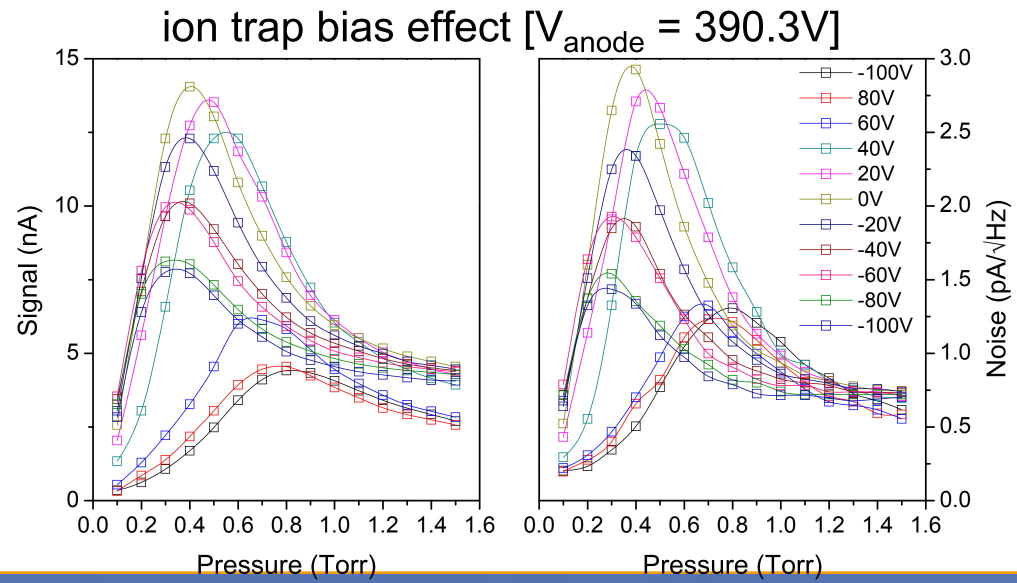


- Model predictions (plot) are in accordance with corresponding ESD images
- FFT image analysis is required to confirm the model predictions

Images on Au on C taken at: 15keV, 100pA, 50kX, 1024x882, 0.4µs (no filters) x64frames

Helix – H_2O vapor

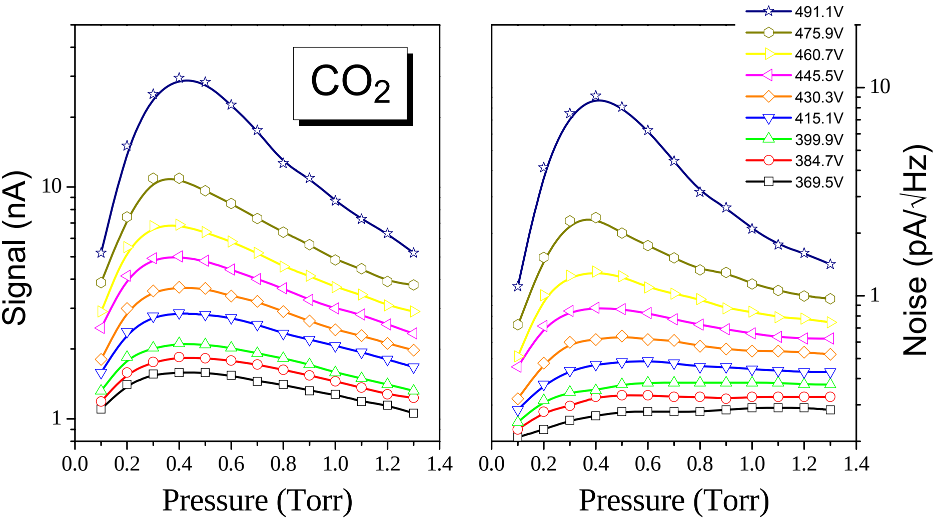

anode bias effect [$V_{ion\ trap}$ = 0V]

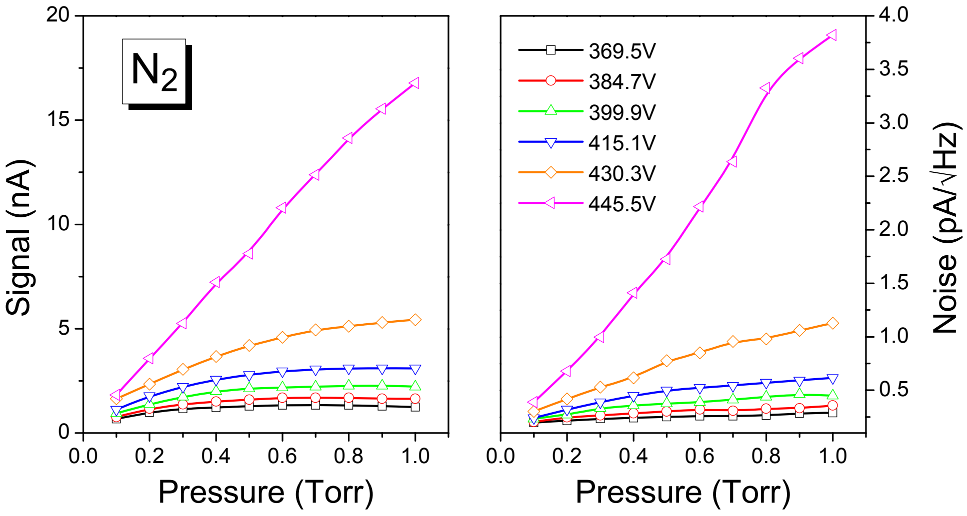

ion trap bias effect [V_{anode} = 390.3V]

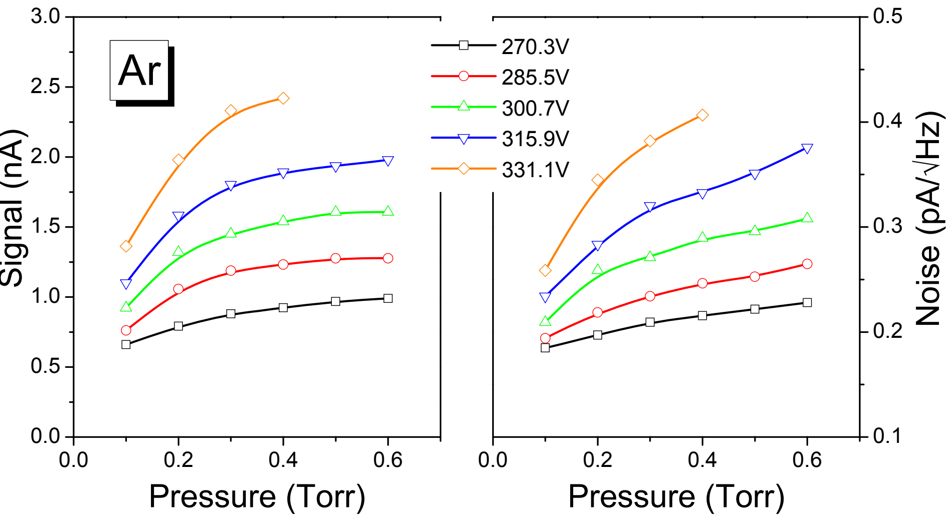
- Signal and Noise exhibit the same characteristics
- Low pressure peak (LPP) centered at ~0.4Torr
- High gains introduce instability in the system
- LPP changes position
  - Positive bias moves the peak at lower pressures
  - Negative bias moves the peak at higher pressures
- Grounded ion trap provides maximum gain (for the conditions investigated)

operating conditions: Eo=5keV, Io=94pA, WD=4mm, B_F=4.0531355 **sample: Pt aperture**

Helix – Gases







- Noise follows signal behavior for all gases
- CO$_2$ shows similar characteristics with H_2O
- N$_2$ and Ar do not exhibit LPP
- Pressure ranges are different for each gas due to lower column vacuum breakdown

operating conditions: Eo=5keV, Io=93pA, WD=3.5mm, Vion trap=0V, B$_F$=4.467958 sample: Pt aperture