中国散裂中子源

SEY studies in CSNS

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CSNS
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Outline

- Background and significance
- Measurement scheme

- SEY and its dependence on incidence angle
- Spatial distribution of secondary emission electrons
- Spectrum distribution of secondary emission electrons
- SEY depression as electron dose deposition

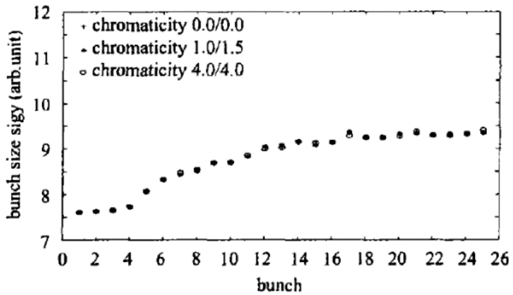
- Design and construct of SEE characteristics platform
- Experimental measurement and theoretical research
- Formula calculation and software simulation
- Summary and prospect

Background and significance

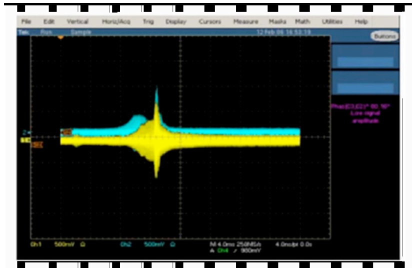
Electron cloud effect and SEE characteristics of material

Impact of electron cloud effect

（1）During the operation of the accelerator, the electron cloud effect in the vacuum pipe can cause **beam instability**, resulting in a decrease in **beam lifetime**, generation of **the detector background** and so on.



Simulated vertical bunch size blowup along the train



BPM traces of beam instability in the SNS accumulator ring

（2）The secondary electron multipacting effect occurring in the **high-frequency cavity** will cause frequent ignition of the high-frequency cavity, which severely limits the electromagnetic field intensity in the high-frequency cavity and even cause the failure of the high-frequency cavity system.

（3）Secondary electron emission **power deposition** in a beam screen in a superconducting low temperature environment may even result in quench protection of the entire superconductor system.

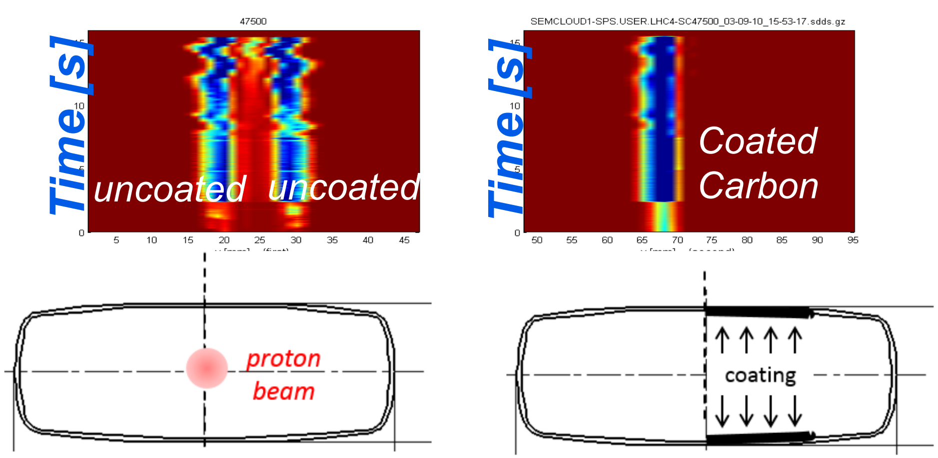
Background and significance

Source of electron cloud effect

（1） Electrons generated by beam loss；
（2） Electrons generated by ionization of residual gases in a vacuum chamber；
（3） Secondary electrons；
（4） For a proton accelerator such as CSNS, the stripping foil in the injection zone also generates a large amount of electrons；

Secondary electron emission （SEE） characteristics of material

The core of electron cloud effect research is to study the establishment process of electron cloud. The generation of secondary electrons plays a decisive role in the process of establishing the electron cloud and the final density. Therefore, this subject studies the secondary electron emission characteristics of the material.



Electron cloud current in the SPS with an electron cloud detector

Background and significance

Vacuum chamber material commonly used in accelerators

Stainless steel

Aluminum

Copper

TiZrV and TiZrHfV

Ceramic coated TiN**(RCS ring of proton accelerator)**: Ceramic can suppress the **eddy current effect** produced by the rapidly changing magnetic field in the magnets of the RCS ring, but the secondary electron emission coefficient of the ceramic is relatively high, so the TiN film is to be plated on the inner wall of the ceramic vacuum chamber.

Background and significance

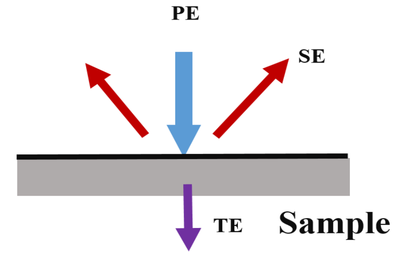
Significance

- Reference for **selecting the best vacuum chamber material**
- Providing measurement data to **improve accelerator coating process**
- Providing data for **simulation of electron cloud**

Measurement scheme

Secondary electron Yield

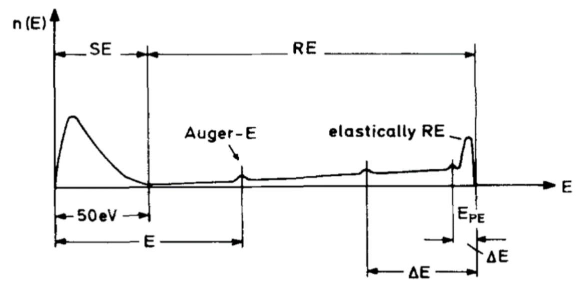
$$\delta = n_{SE} / n_{PE}$$



Complete secondary electron emission characteristics

SEY and its dependence on incidence angle
Spatial distribution of secondary emission electrons
Spectrum distribution of secondary emission electrons
SEY depression as electron dose deposition

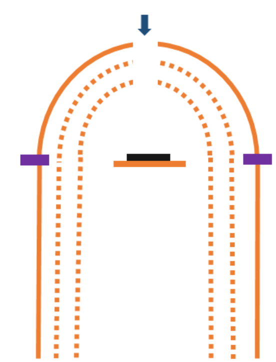
REY=EREY+IREY
TSEY=SEY+REY



Core: detector and sample holder

The detector is a three-layer structure: the outermost cap detector and wall detector are connected by an insulating ring, and the middle layer and the innermost layer are grid structures.

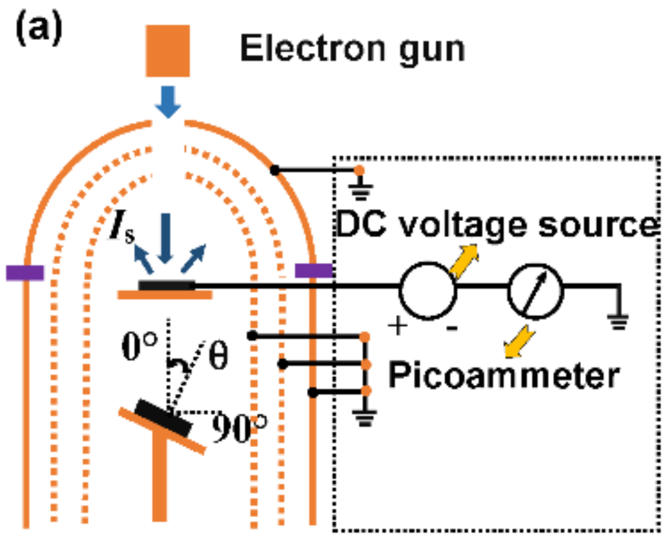
Sample holder: can be moved up and down in the vertical direction, and can be rotated in the axial direction from 0 to 180 degrees



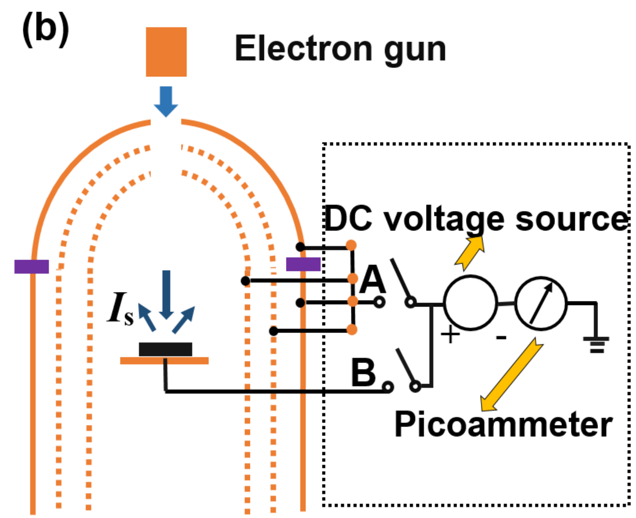
Measurement scheme:
SEY and its dependence on incidence angle

- **Conductive sample**

Sample method： -20V bias on sample→ I_t and +100V bias on sample→ I_p， $\delta=1-I_t/I_p$
Collector method： +50V bias on collector → I_s， +50V bias on collector and sample → I_p, $\delta=I_s/I_p$



Sample method



Collector method

Measurement scheme:
SEY and its dependence on incidence angle

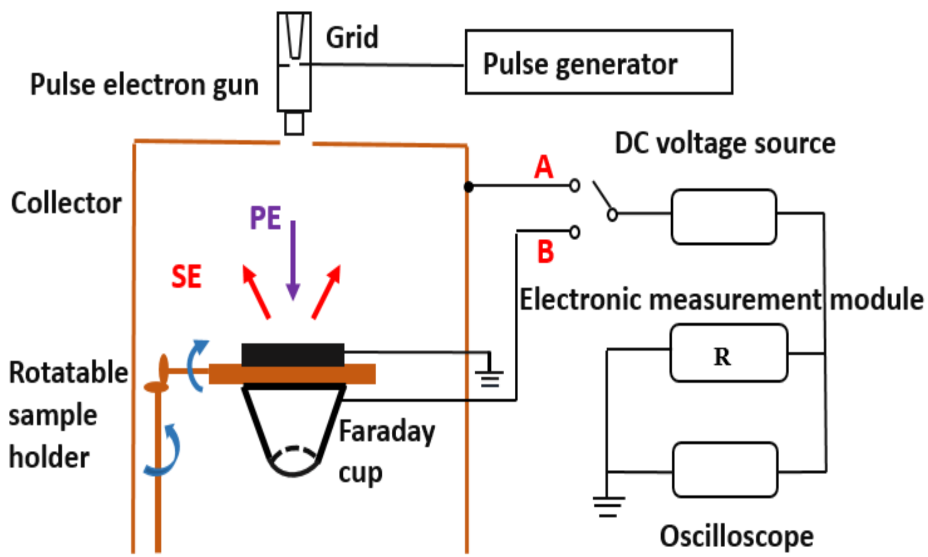
➢ Insulating sample

(1) Impulsator : 150 μs, f=25 Hz TTL signal ;

(2) Faraday cup up, add + 45 V bias on Faraday cup, single pulse mode, the pulse width is 150 μs, incident electron current is I_p;

(3) Sample up, add +45 V bias on the complete detector, single pulse mode, secondary electron current I_s;

(4) Before the next measurement, neutralize the charge accumulated on the sample surface: add -45V bias on the collector, periodic pulse mode, pulse duration 1~ 5s, so that the secondary electron can return to the sample surface .

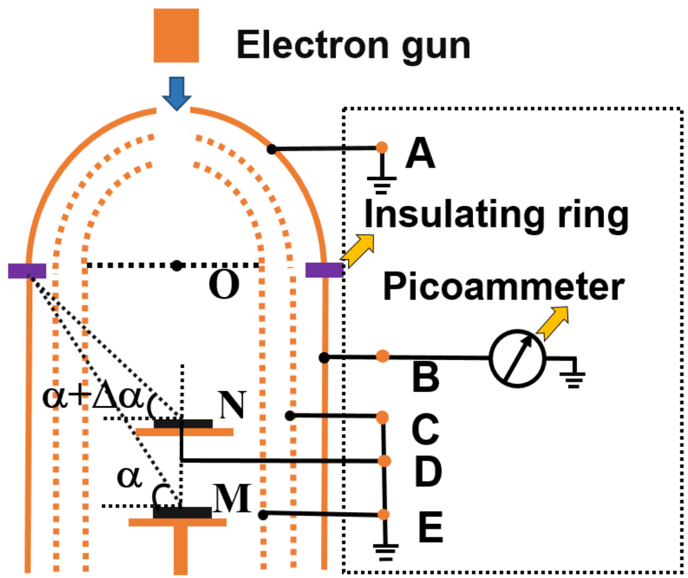


Neutralization method with negative bias on collector

Measurement scheme:
Spatial distribution of secondary emission electrons

Core: move the sample to different vertical positions to measure the current change on the cylinder type sidewall detector.

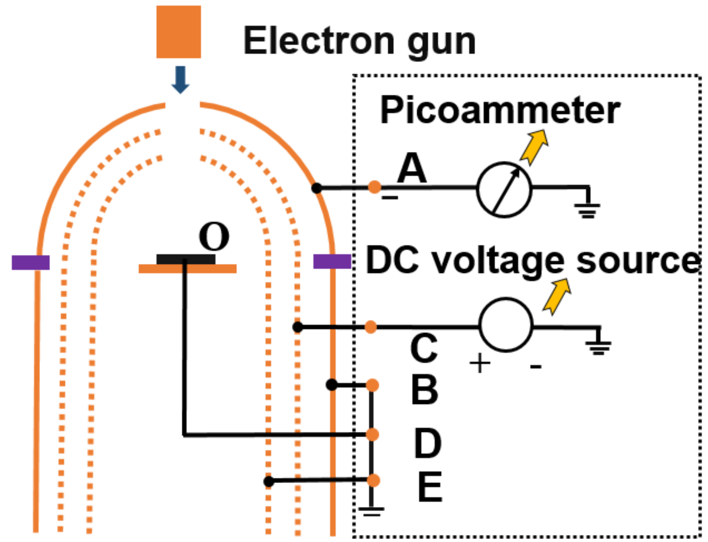
Method: M → α, I_α; N → $I_{\alpha+\Delta\alpha}$, $\Delta\alpha$ and $\Delta I_\alpha = I_\alpha - I_{\alpha+\Delta\alpha}$, 20° ~60°, 1°。



Difference method

Measurement scheme:
Spectrum distribution of secondary emission electrons

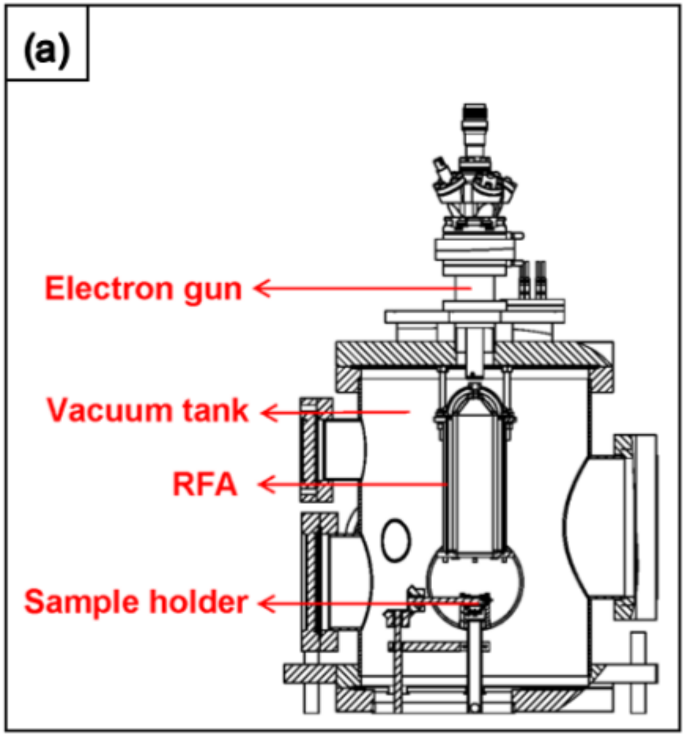
The sample table is placed at the center of the hemispherical detector. By changing the grid voltage U, the secondary electrons with energy less than eU are prevented, draw E（eU）-ΔI_s curve as pectrum distribution .

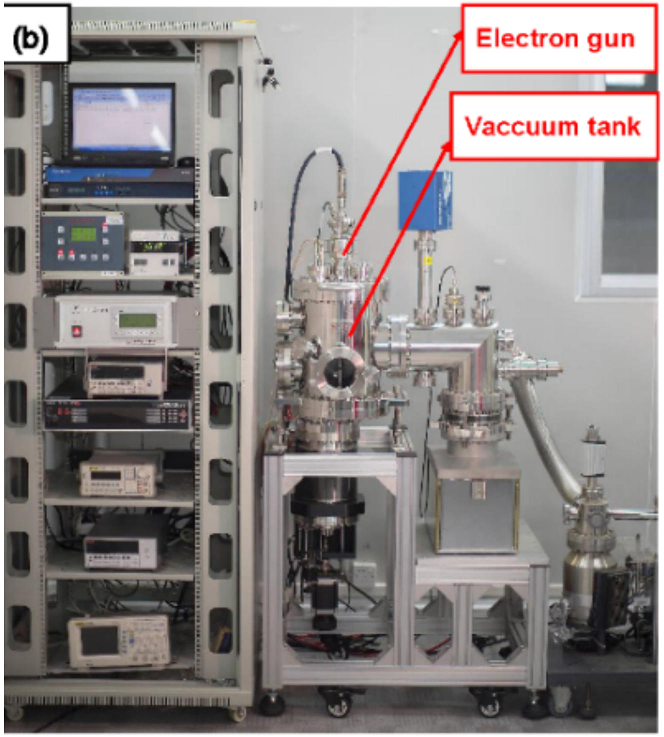


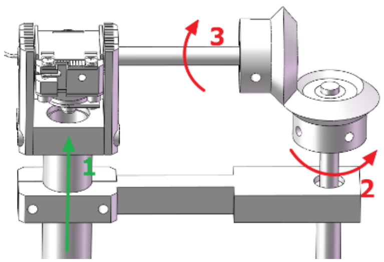
Retarding field method

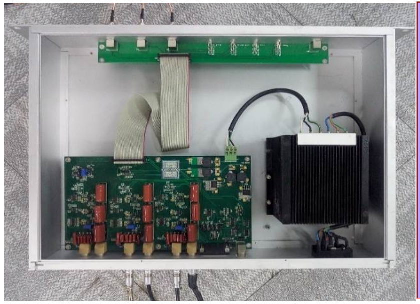
Design and construct of SEE characteristics platform

Measuring platform: vacuum system, measuring circuit system, data acquisition and equipment control system





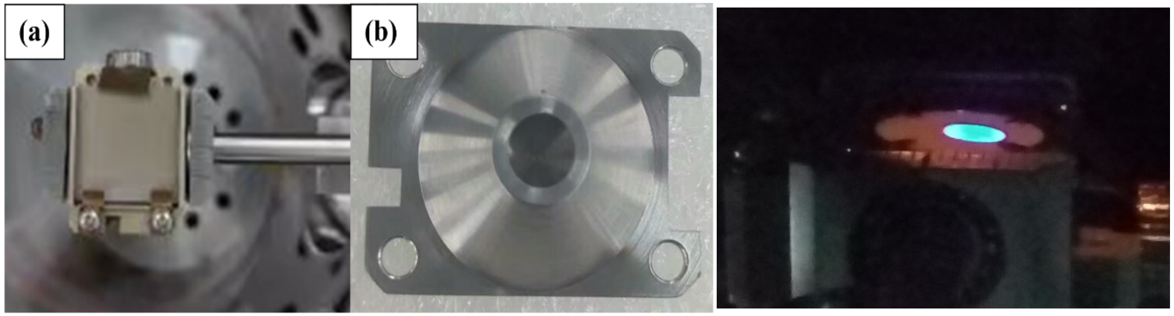




Design and construct of SEE characteristics platform

Device advantage

- On the back of the rotatable sample holder, faraday cup(insulation sample measurement) and fluorescent target (focusing adjustment) can be installed according to the experimental requirements.

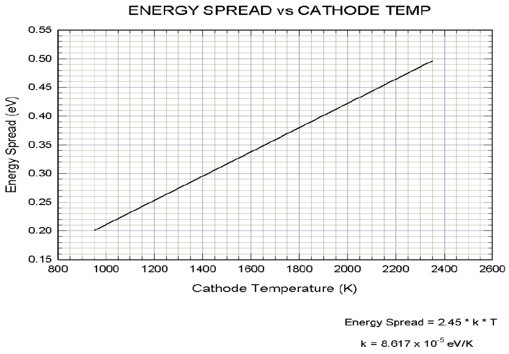


- Can measure the entire spatial distribution of secondary electrons
- Can measure the entire energy spectrum distribution of secondary electrons

Experimental measurement and theoretical research

Kimball Physics EFG-7-6644 elctron gun

Beam Energy	100 eV-5000 eV
Beam Current	1 nA-100 μA
Energy Spread	Approx 0.5 eV cathode thermal spread, calculated
Spot Size	1 mm-100 mm



Temp (K)	ES (eV)
950	0.201
1000	0.211
1050	0.222
1100	0.232
1150	0.243
1200	0.253
1250	0.264
1300	0.274
1350	0.285
1400	0.296
1450	0.306
1500	0.317
1550	0.327
1600	0.338
1650	0.348
1700	0.359
1750	0.369
1800	0.380
1850	0.391
1900	0.401
1950	0.412
2000	0.422
2050	0.433
2100	0.443
2150	0.454
2200	0.464
2250	0.475
2300	0.486
2350	0.496

（1） Energy stability： ±0.01% per hour ±0.02% per 8 hours at full output； The dispersion of energy varing with filament temperature is as shown;
Energy dispersion refers to the range of fluctuations centered around the set energy.

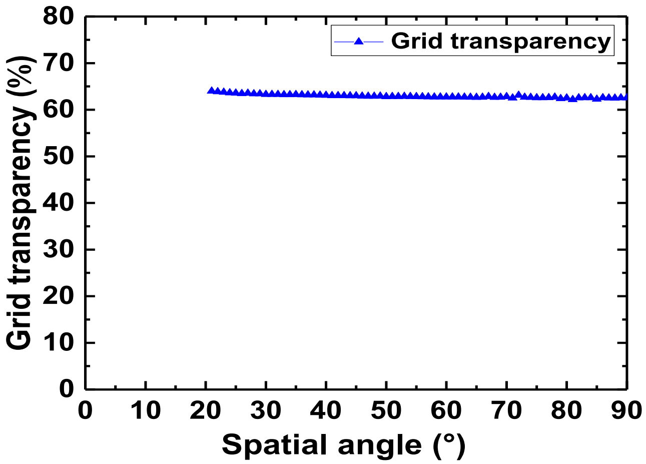
（2） beam stability： After warm up， ±0.1% per hour with Emission Current Control (ECC) or±10% per hour without ECC

Experimental measurement and theoretical research

Grid transparency :

manufacturer :76％(vertical),
experimental measurement: 63%

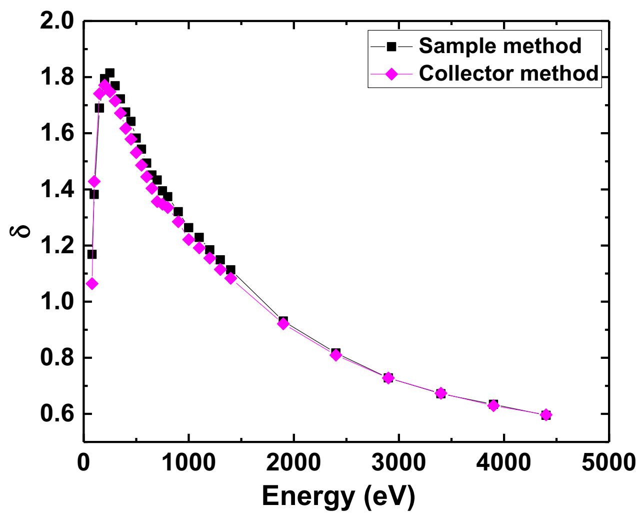
Secondary electron spatial distribution is measured by secondary electron current's relative variation under different spatial angle, and the range of almost constant grid transparency does not affect the measurement result.



Experimental measurement and theoretical research: Comparison of sample method and collector method

Conclusion： The measurement results of the two methods are close , consistent with reference（Valizadeh, Reza, et al.2014）

The sample method is easy to realize automatic measurement and control.



Cu	Epm（eV）	δm
sample method	300	1.80
collector method	300	1.70
Valizadeh, Reza, et al.2014	300	1.9

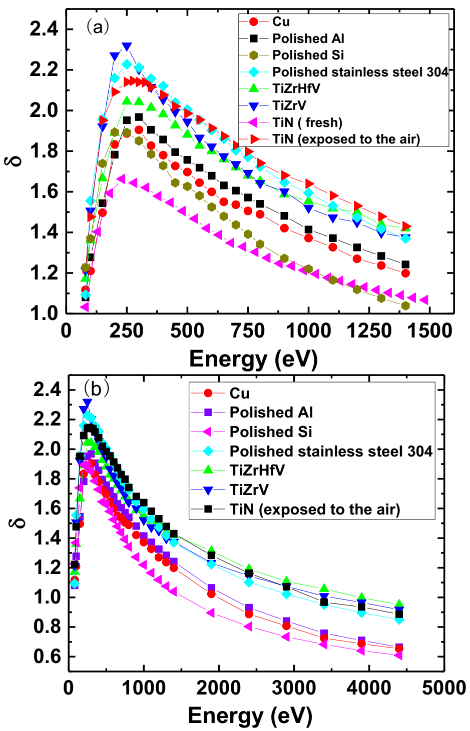
Experimental measurement and theoretical research: SEY

- Conductive sample

I_p=300 nA

Conclusion: TiN（fresh）<polished Si<Cu<polished Al< TiZrHfV(nonactivated) < TiN（exposed）<Polished stainless steel 304< TiZrV(nonactivated). E_{pm}:250 -300 eV

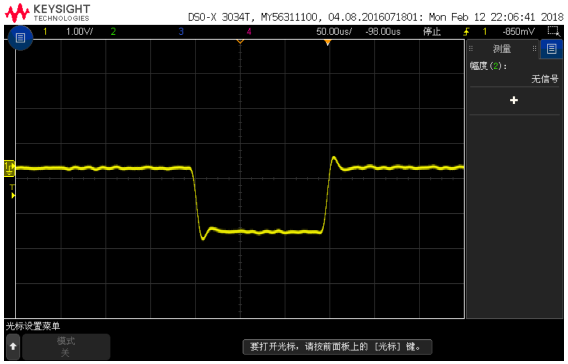
Due to the material of SEY is not only related to the material composition but also surface roughness , surface pollution and so on, the measurement results of the same material under different measuring condition and different devices will have differences.

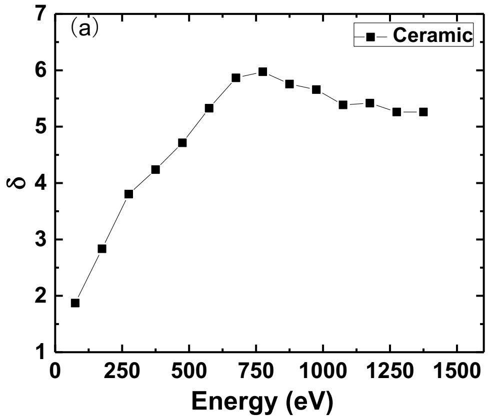


样品	E_{pm}（eV）	δ_m	E_{pm}（eV）（reference）	δ_m（reference）
TiN（fresh）	230	1.66	300	1.5~2.4
Polished Si	200	1.89		
Cu	300	1.90	300	1.90
Polished Al	300	1.97	300	2.55
TiZrHfV	250	2.04		
TiN（expose for 3 month）	275	2.15	300	1.5~2.4
Polished stainless steel 304	250	2.23	300	2.25
TiZrV	250	2.32	250	1.3~2

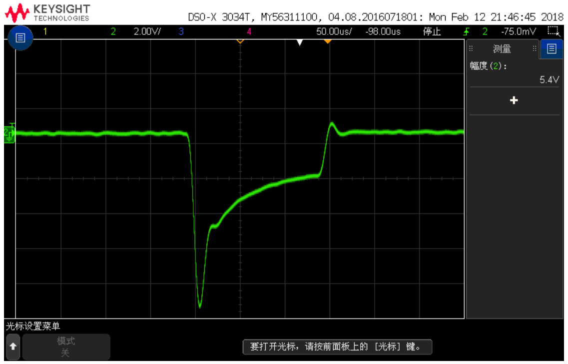
Experimental measurement and theoretical research: SEY

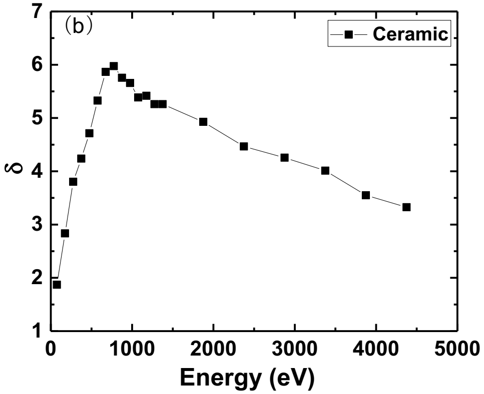
- Insulating sample





Voltage signal Up at faraday cup measured by oscilloscope





Voltage signal Us at the collector measured by oscilloscope after neutralization

SEY of ceramic samples

Experimental measurement and theoretical research: SEY

- Insulating sample

Conclusion: The SEY of ceramic sample is very high, Primary energy 75 eV → 1.9, Epm:775 eV → 5.97, constant with Dawson, P. H., 1966(6.4).

In order to reduce the eddy current effect on the vacuum chamber surface caused by the rapidly changing magnetic field in magnet in CSNS, ceramic is used as vacuum chamber material in the RCS ring, but the electron cloud effect caused by the high secondary electron yield will affect the stability of the proton beam, so the inner wall of the ceramic vacuum chamber was then plated with TiN films of suitable thickness with good vacuum properties and low secondary electron emission coefficient.
After coated with TiN, 5.97 → 1.66, rose to 2.15(exposed to the air for 3 month) due to contamination.

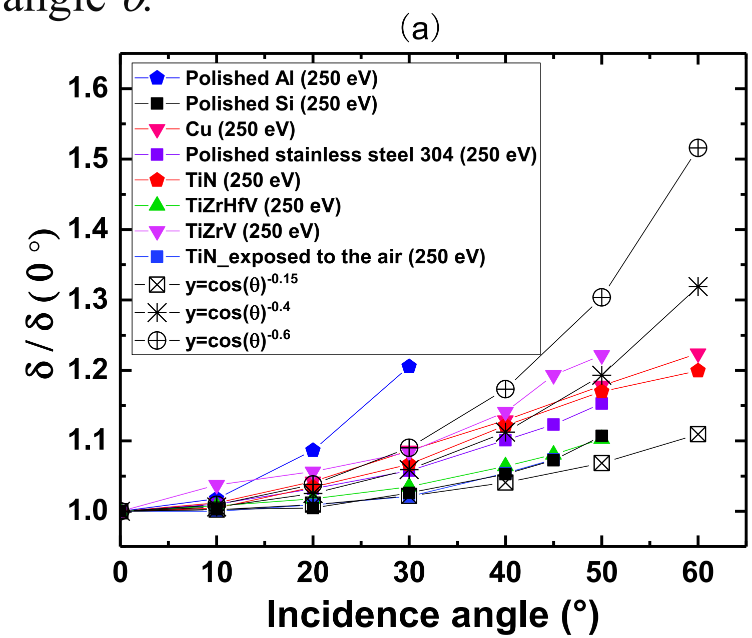
Sample	E_{pm}（eV）	δm	E_{pm}（reference）	δm（reference）
ceramic	775	5.97	650	6.4
Coated with TiN（fresh）	230	1.66	300	1.5~2.4

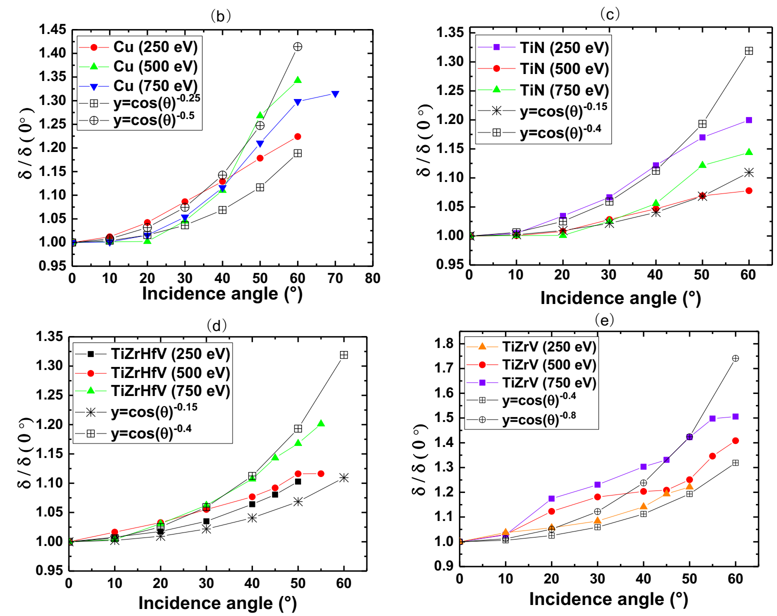
Experimental measurement and theoretical research: SEY's dependence on incidence angle

- Oblique incidence

Conclusion: In the range of 0-60°, the SEY gradually increases with the increase of the incident angle θ, and has a cosine relationship with the incident angle. However, the SEY begins to decrease after the incident angle increased to 60°, which is consistent with the reference (Lin Zulun, 2013).

This may be because the measurement error increase with the increase of the incident angle θ.





Experimental measurement and theoretical research: SEY's dependence on incidence angle

Comparing the measurement results with the calculation results of the cosine function formula, it can be seen that the corresponding coefficients n of several materials range from about 0.16 to 0.80:

$$y = \cos(\theta)^{-n}$$

Where n is a parameter related to the material and the energy of the incident electrons.

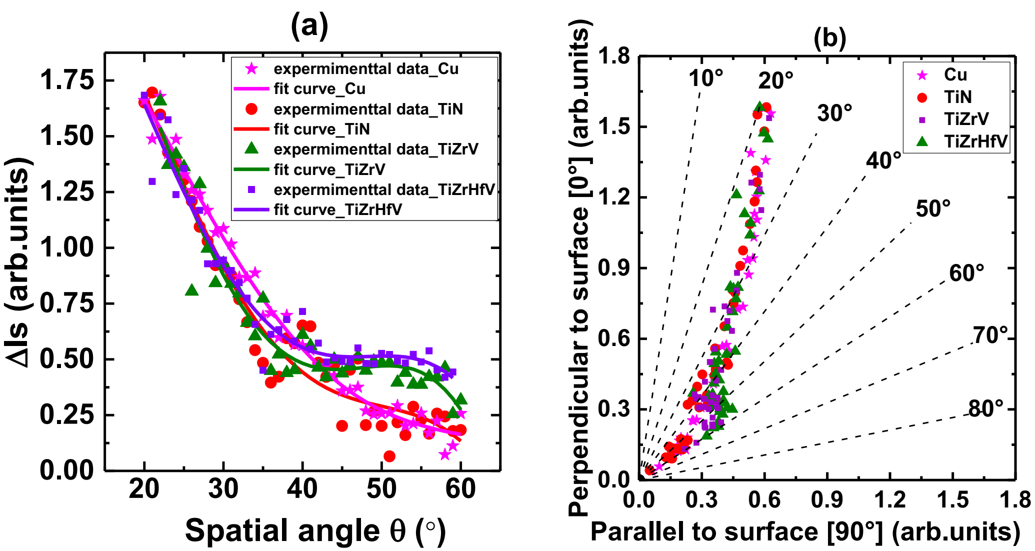
Sample	*n*
Cu	0.25~0.50
TiN	0.15~0.40
TiZrHfV	0.15~0.40
TiZrV	0.40~0.80

Experimental measurement and theoretical research: Spatial distribution of secondary emission electrons

***E*p=600 eV，*I*p=500 nA**

Conclusion: According to the theory (Ciappa et al., 2012), the number of true secondary electrons at the unit solid angle conforms to the following formula. The parameters obtained by fitting the measurement results using the formula are shown in the following table.

$$f(\theta) = \cos\theta(1 + a\sin^2\theta + b\sin^4\theta + \ldots)$$



Secondary Electron Spatial Distribution in Cartesian and Polar Coordinate Systems

	a	b
Cu	-2.10	1.63
TiN	-1.24	1.91
TiZrHfV	-1.09	2.03
TiZrV	-0.96	1.99

Fitting parameters for different samples

Experimental measurement and theoretical research: Spatial distribution of secondary emission electrons

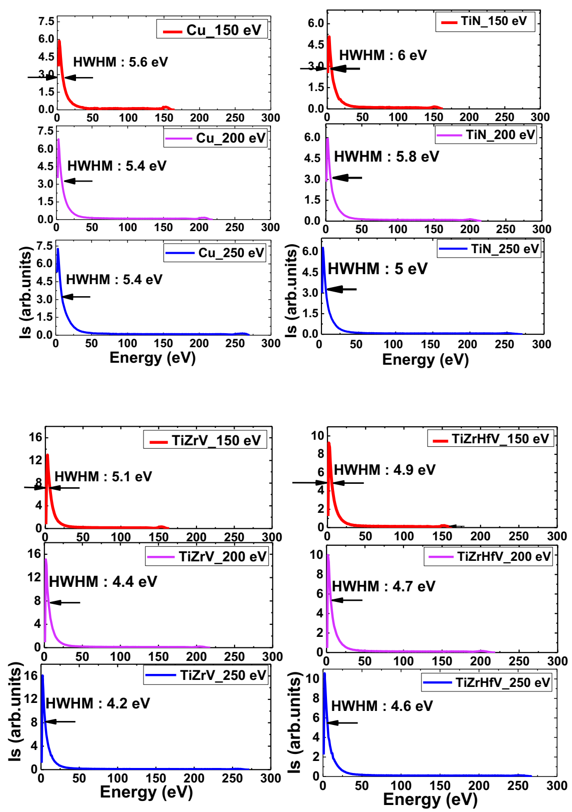
- **Measure the complete energy spectrum of secondary electrons and determine the proportion of different kinds of secondary electrons；**
- **Calculated the full width at half maximum （FWHM） of the true secondary electron peak and the elastic reflected electron peak;**
- **Using the gaussian function to fit the secondary electron peak and the elastic reflected electron peak.**

Experimental measurement and theoretical research: Spectrum distribution of secondary emission electrons

- **Measure the complete energy spectrum of secondary electrons and determine the proportion of different kinds of secondary electrons**

Conclusion:

0 ~ 50 eV(secondary electron peak), E_p(elastic scattering peak),



Total secondary electron energy spectrum of different materials

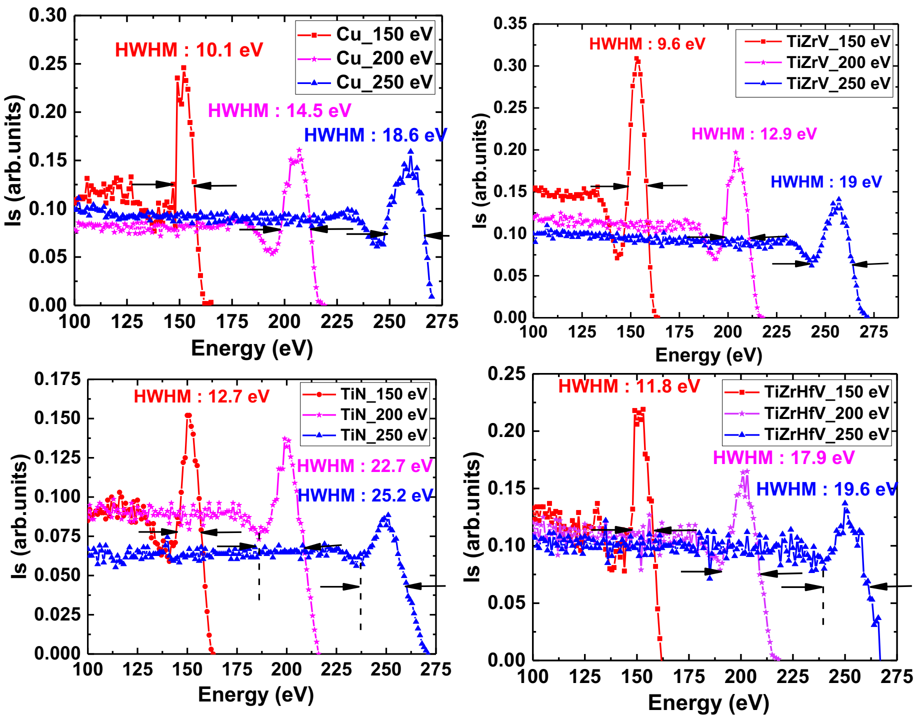
材料	E_p（eV）	SE	ERE	IRE
Cu	150	80.2%	4.8%	15.0%
	200	79.9%	3.1%	17.0%
	250	76.8%	2.9%	20.3%
TiN	150	81.8%	3.3%	14.9%
	200	78.7%	3.5%	17.8%
	250	78.5%	3.0%	18.5%
TiZrHfV	150	83.5%	3.1%	13.4%
	200	80.7%	2.7%	16.6%
	250	78.5%	2.4%	19.1%
TiZrV	150	84.8%	2.8%	12.4%
	200	84.2%	2.2%	13.6%
	250	83.3%	1.8%	14.9%

The proportion of secondary electrons in each component （80%，3%， 17%）

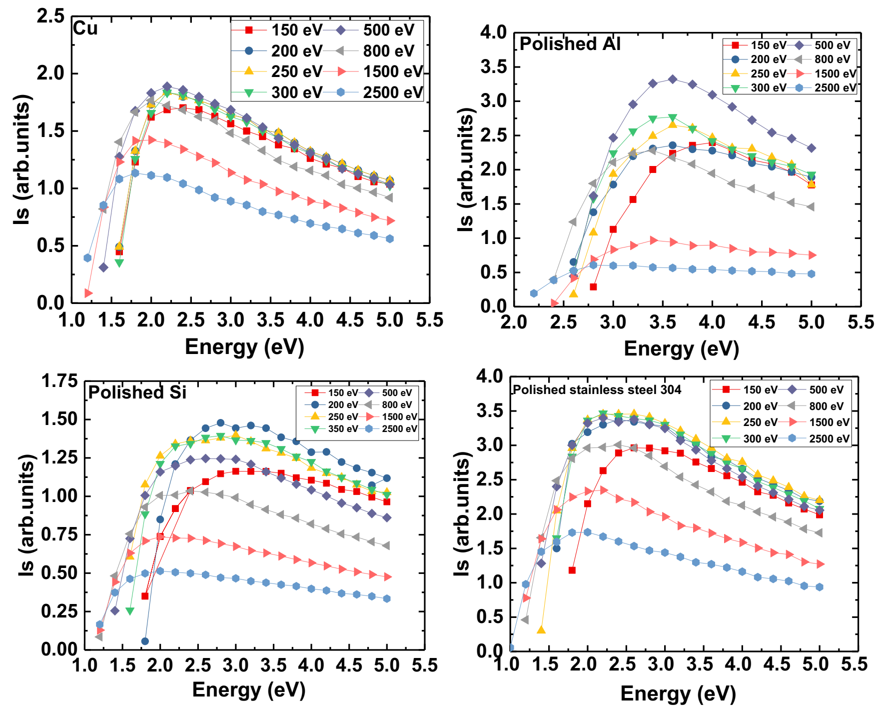
Experimental measurement and theoretical research

The position of the true secondary electron peak changes very little with the change of the energy of the incident electron, but the position of the elastic scattering peak increases with the increase of the energy of the incident electron.

Generation mechanism: extranuclear electron, primary electron



Elastic scattering electron energy spectrum of different materials



True secondary electron energy spectrum of different materials

Experimental measurement and theoretical research

- **Calculated the full width at half maximum （FWHM） of the true secondary electron peak and the elastic reflected electron peak;**

Conclusion: the position of energy spectrum peak is consistent with reference, and the half height and width is slightly larger than that of reference （Staib, Ph, and U. Dinklage，1977）

Ep (eV)	Cu	Al	Si	Stainless steel 304	TiN	TiZrV
150	2.4	4.0	3.0	2.6	2.8	2.4
200	2.2	3.6	3.2	2.4	2.6	2.2
250	2.2	3.6	3.0	2.4	2.6	2.2
300	2.2	3.6	2.8	2.2	2.6	2.2
500	2.2	3.6	2.6	2.2	2.4	2
800	2.0	3.4	2.6	2.4	2.4	1.8
1500	2.0	3.4	2.0	2.2	2.0	1.6
2500	1.8	3.2	2.0	2.0	1.8	1.8

The position of the true secondary electron energy spectrum peak (eV) （2~4eV）

样品	Ep（eV）	SE（eV）	ERE（eV）
Cu	150	5.6	10.1
	200	5.4	14.5
	250	5.4	18.6
TiN	150	6.0	12.7
	200	5.8	22.7
	250	5.0	25.2
TiZrHfV	150	4.9	11.8
	200	4.7	17.9
	250	4.6	19.6
TiZrV	150	5.1	9.6
	200	4.4	12.9
	250	4.2	19.0

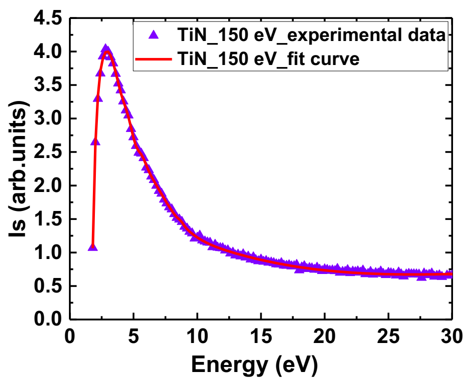
True secondary electron and elastic scattering electron energy spectrum half high and wide (5 eV， 16 eV)

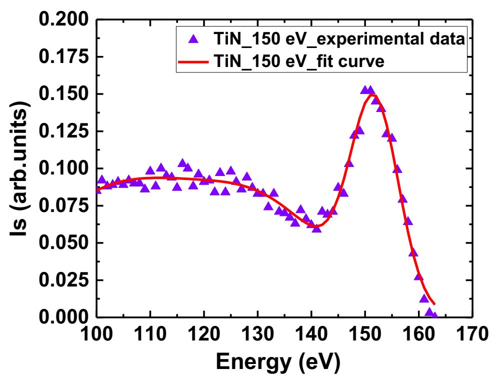
Experimental measurement and theoretical research

- **Using the gaussian function to fit the secondary electron peak and the elastic reflected electron peak**

Satisfy: gaussian distribution; For: simulation of electron clouds

$$f(\mathrm{x}) = a_1 \times e^{-\left(\frac{x-b_1}{c_1}\right)^2} + a_2 \times e^{-\left(\frac{x-b_2}{c_2}\right)^2} + a_3 \times e^{-\left(\frac{x-b_3}{c_3}\right)^2} + ..$$





TiN	a	b	c
1	-8.571e+004	-2.866	1.435
2	0.1676	4.559	0.5111
3	0.07829	5.701	0.3892
4	0.8744	4.833	3.082
5	1.425	122.1	103.8
6	0.02801	8.723	0.2728
7	1.664	2.793	1.48
8	2.352	-11.7	20.05
Goodness of fit (SE)			
SSE	0.001698		
R-square	0.9676		
Adjusted R-square	0.9629		
RMSE	0.005557		

TiN	a	b	c
1	0.1309	151.8	6.322
2	0.08781	105.3	25.11
3	0.05302	132.9	17.1
Goodness of fit（ERE）			
SSE	0.0546		
R-square	0.9995		
Adjusted R-square	0.9994		
RMSE	0.02151		

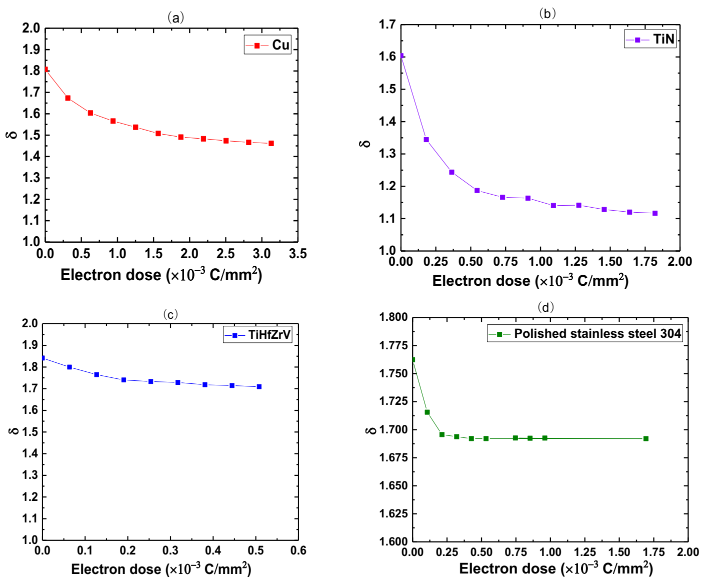
Experimental measurement and theoretical research

***E*p=250 eV， *I*p=0.6 μ A**

Conclusion: the SEY of each material decreases with the increase of incident electron dose and finally becomes stable.

Analysis : Electron bombardment can cause changes in the surface of the material, removing contaminants and oxides on the surface of the material, and even forming a carbon film on the surface, making the measured SEY lower (Larciprete R, 2013).

Bombardment reducing SEY is an effective secondary electron suppression measure.



Sample	δ_0	δ	Dose（×10^{-3}C/mm^2）
Cu	1.81	1.46	3.13
TiN	1.60	1.12	1.82
TiHfZrV	1.84	1.71	0.51
Stainless steel 304	1.76	1.69	0.96

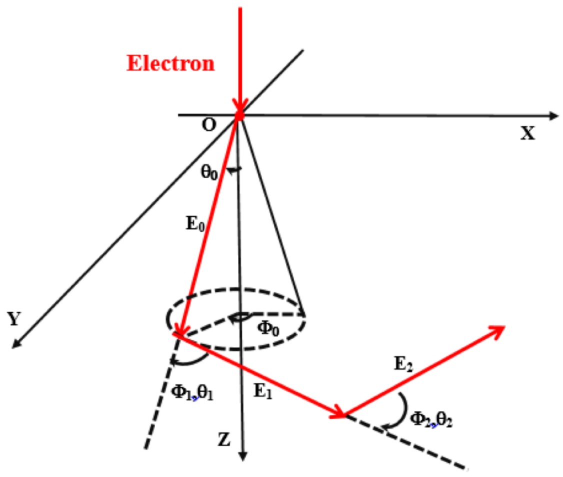
Formula calculation and software simulation

- **Formula**

$$\delta_{e\theta} = \frac{K}{\varepsilon}\int_{0}^{\frac{1}{\alpha\cos\theta}} \frac{G}{E_{P0}} e^{-\alpha s\cos\theta} ds = \frac{KG(e-1)}{\varepsilon e E_{P0}\alpha\cos\theta} \qquad (1)$$

$$\delta = 0.5 \times \frac{E_{P0}}{\varepsilon} \times \frac{\lambda}{R}(1 - e^{-R/\lambda}) \qquad (2)$$

$$\frac{\delta}{\delta_m} = 1.28\left(\frac{E_P}{E_P^m}\right)^{-0.67}\left(1-\exp\left(-1.614\left(\frac{E_P}{E_P^m}\right)^{1.67}\right)\right) \qquad (3)$$



- **Casino**

Based on Monte Carlo simulation method： A computer experimental method for simulating the motion of real particles using the idea of probability statistics.

（DEMERSH， 2011）

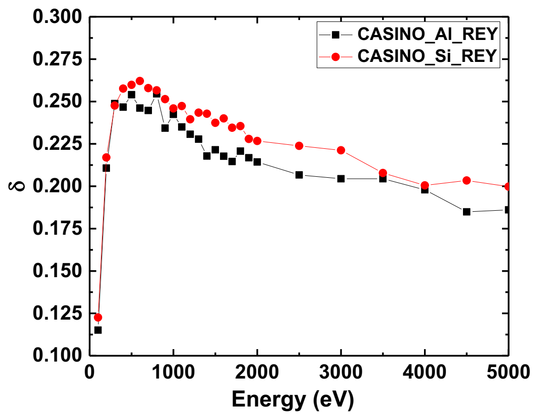
Formula calculation and software simulation: SEY

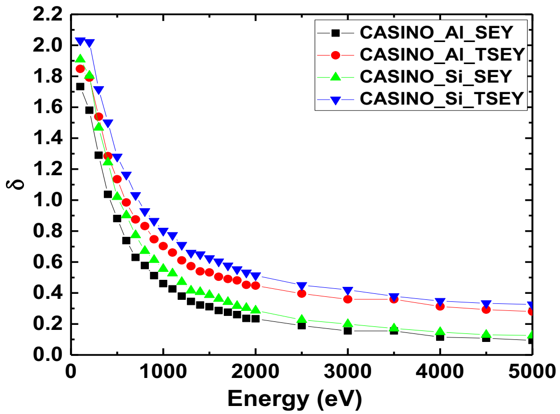
- **CASINO**

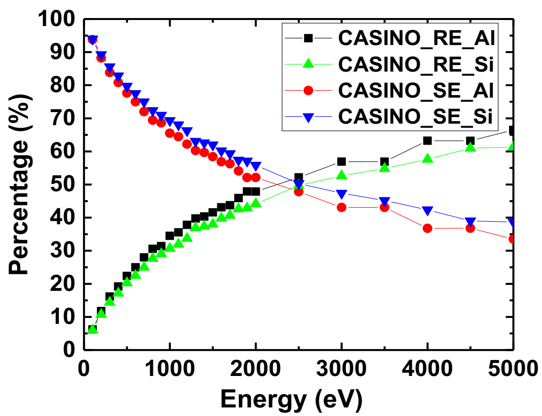
Conclusion:

As the energy of the incident electrons increases, the yield of backscattered electrons first increases and then decreases, and the yield of true secondary electrons(SE) and the total secondary electrons(TSE) continue to decrease. As the incident electron energy increases, the proportion of true secondary electrons (SE) decreases, and the proportion of reflected electrons (RE) increases.

The work function used in the simulation is the default value of the software, Al is 4.28 eV and Si is 4.85 eV







Formula calculation and software simulation:SEY

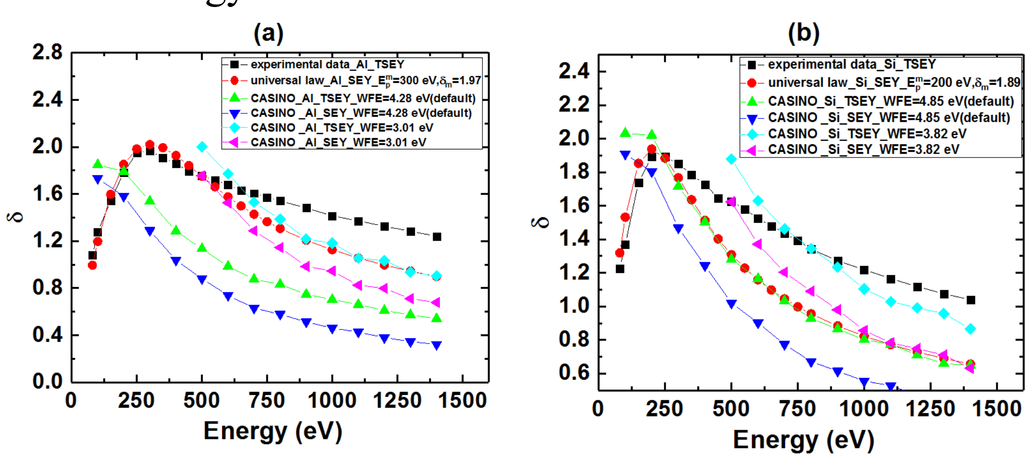
The calculation result of formula (3) is consistent with the trend of experimental measurement results. Software simulation is consistent with experimental data after 500 eV. The numerical differences are as follows:

$$\frac{\delta}{\delta_m}=1.28\left(\frac{E_P}{E_P^m}\right)^{-0.67}\left(1-\exp\left(-1.614\left(\frac{E_P}{E_P^m}\right)^{1.67}\right)\right) \qquad (3)$$

①The theoretical formula is a result of a series of formulae approximate derivation, so there is a certain gap between the true value.

②The theoretical formula and software simulation only consider the nature of the sample material itself, and do not consider the state of surface contamination, adsorption, roughness, etc. Therefore, there is a certain gap between the actual value and the actual value。

③In the theoretical formulas and software simulations, true secondary electron yields are calculated, however the experiment measures the total secondary electron yield. The value of the total secondary electron yield is the sum of the true secondary electron yield value and the value of the backscattered electron yield. From the measurement analysis, it can be seen that the proportion of backscattered electrons increases with increasing incident energy. Therefore, the experimental measurement is slightly larger than the calculated value of the formula and the difference between the two increases gradually with the increase of energy.



Summary and Prospect

Summary

- The differential method was used to verify the measurement scheme of the secondary electron spatial distribution, and a multi-functional, high-efficiency secondary electron emission characteristic measurement platform capable of simultaneously measuring secondary electron yield, energy spectrum distribution, and spatial distribution was constructed.

- TiN（fresh）<polished Si<Cu<polished Al< TiZrHfV(nonactivated) < TiN（exposed）<Polished stainless steel 304< TiZrV(nonactivated)<ceramic. Epm:250 -300 eV,δm:1.66~2.32， ceramic after coated with TiN, 5.97 → 1.66

- δ has a cosine relationship with the incident angle in 0~60° .

- The spatial distribution satisfies cosine distribution.

- The spectrum disrtribution satisfies gaussian distribution

- SEY of each material decreases with the increase of incident electron dose and finally come to be stable

Summary and Prospect

Prospect

- **Further study on the new materials such as graphene**
- **Add heating and baking equipment**
- **Add low temperature superconducting equipment**
- **Upgrade to on-line measuring device**

Thank you for your attention and advice!