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NUMERICAL OPTIMIZATION OF IONIZATION GAUGE WITH CNT EMITTER

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Abstract **–** Electron stimulated desorption (ESD) and hot cathode effects are the key factors for extending the lower limit of ultra-high vacuum (UHV) measurement. Based on the ions optic simulation software Simion 3D 8.0, the mechanism of energy filter in axial-symmetric transmission (AT) gauge has been analysed. And the influence of potential distribution within anode grid on ions collection efficiency is studied, which also verified by the experiment. Then a new carbon nanotube based gauge with energy filter is constructed for eliminating hot cathode effects and ESD ions. To improve sensitivity and decrease ESD effect, electrodes structure (i.e. high voltage gate, energy suppressor etc.) and voltages are optimized by numerical simulation. The results show that suppressor could decrease the electric field penetration effect of high voltage gate. The cylindrical energy filter could decouple ESD ions from gas ions by means of energy differences between two kinds of ions.

Keywords: ionization gauge, carbon nanotube emitter, electron stimulated desorption, sensitivity, simulation

1. INTRODUCTION

For ultra-high vacuum measurement, hot ionization gauge is one of useful devices. However, kinds of problems caused by hot filament, such as saturation vapor pressure, light irradiation, thermal radiation etc., impose restrictions on its applications. Recently, lots of requirements , such as low consumption, rapid response, no heat effect, have been proposed in space science, high energy physics, and so on. So lots of researches on “cold” field emitters based ionization gauges have been reported in recent years[1]. Especially, the carbon nanotube (CNT) emitter shows novel characteristics, such as working in room temperature, rapid response, low consumption and rare heat outgassing, and so on. So the hot cathode effect has been well overcome. Dong C K etc. has studied CNT emitter based extractor gauge with meaurable range of 10^{-5} Pa-10^{-8} Pa, and analyzed the outgassing in the gauge[2]. It showed that outgassing contribution come from the gauge anode and the CNT emitter could be negligible.The pressure rise is mostly due to desorption of hydrogen, CO_2, CO and O_2, which are the main ESD ions sources. Consequently, electron stimulated desorption (ESD) is one of the key factors to affect the lower limit extension for CNT based gauge. Whereas, for hot cathode ionization gauge, several effective methods have been used for minimizing the error contribution of ESD ions. In 1965, Redhead developed extractor gauge, which reduced ESD and soft X–ray. Then for reducing the ESD ions collection efficiency to a lower level, Akimichi etc. employed a cylindrical energy filter and developed axial-symmetric transmission (AT) gauge which extend the lower limit to 5×10^{-11}Pa. Moreover, such as cylindrical deflection electrode, electron bombardment, anode grid ohmic heating, etc., were also used to minimize ESD contribution[3].

In the paper, CNT emitter and energy filter were combined and studied. The numerical method was proposed to analyze mechanism of energy filter in AT gauge. The experimental verification was also carried out. Then based on the AT gauge, a finite element model of CNT based ionization gauge was constructed. Electric field distribution and microscopic particle motion characters were analyzed, and the variation of sensitivity, ESD ions etc. were analyzed. The work was important for developing a new CNT based ionization gauge.

2. SIMULATION AND EXPERIMENT

2.1. Basic theory

To study the principle of energy filter, the 3D model and finite element grids of AT gauge are generated by aids of ions optic software Simion 3D 8.0[4]. Overall number of hexahedron grid unit approaches to 10^8. After ignoring the effect of space charge, the finite difference over-relaxation iteration methods are used to solve Poisson equation for analyzing electric field and potential distribution. The trajectories of electric particles are calculated by classical Runge-Kutta method, and the overall path length is calculated by “User Program” module. According to the trajectories of electric particles, the collected ions to overall ions ratio, defined as collection efficiency, could be calculated statistically. In the simulation, gas ions (initial energy 0 eV) distributes randomly in internal space of anode grid (namely ionization space). ESD ions (initial energy 5-7 eV) distributes randomly on the anode grid surface[5]. Because of axis transmission structure for anode grid, ESD ions are set on the surface of one wire. The ESD ions originated from top and bottom rings could collide with screen and annihilate, so they are not considered in calculation. In the simulation, numbers of ESD ions emitted from grid wire and gas ions in ionization space could be calculated statistically.

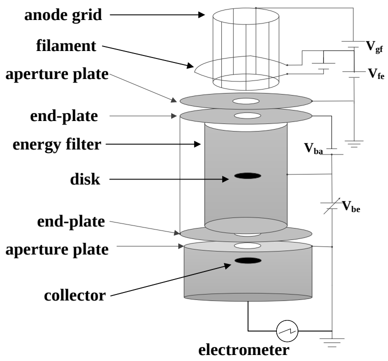
In addition, according to the work mechanism of hot ionization gauge, sensitivity is the key factor to influence the lower limit extension. It relates with gauge structure, electrodes voltages, environment temperature, and so on. Higher ions current could be detected if sensitivity is higher in the condition of the same emission current. In the calculation, electrons (initial energy is 0 eV) distributes randomly on surface of emitter. After emitting from emitter surface, electrons oscillate in ionization space under the action of electric field. The length of electrons trajectories L are used for calculating the sensitivity. Formula (1) shows definition of sensitivity. Path length L and ionization cross section σ for specific gas are all considered in it. With regard to the ionization cross section σ, the electron-impact ionization experiment of various gases was reported by John T. Tate et al. [6]

$$S = \frac{L\sigma}{kT} \quad (1)$$

2.2. Experimental measurement

Axial symmetric transmission (AT) gauge consists of ring filament, anode grid, cylindrical energy filter and collector, as shown in fig.1. Anode grid is Ø12 mm×20 mm. Energy filter is Ø12 mm×35 mm, and a disk with diameter 6 mm is suspended in the center of filter. Two pieces of end-plates with Ø3 mm holes are placed at both ends of the filter. And another two grounded aperture plate are placed outside the end-plate. The filament voltage V_{fe}, anode voltage (V_{fe} + V_{gf}), V_{ba} are 10V, 110V, 300V respectively. Energy filter optimal potential V_{be}, potential V_{ba} between end-cap and energy filter, develop deflecting electric field which would prevent ESD ions but help gas ions to pass through the filter.

In the experiment, a AT gauge is investigated in vacuum-calibration apparatus with ultimate pressure of 7.89×10^{-10} Pa. The ion current is monitored by electrometer (Keithley model 6517A). The pin corresponding to energy filter is connected to high voltage power source (Keithley model 2290-5). All the other electrodes are regulated by commercial controller (AxTRAN, ISX2, ULVAC Inc.). A Leybold IE514 extractor gauge is used to monitor system total pressures. When the base pressure reaches to 2.3×10^{-9}Pa, the filter voltage V_{be} is swept from 0～150 V, and step size defaults to 1 V. The collected ions is monitored and recorded by electrometer. The variation of ions current along with energy filter potential V_{be} is analyzed.



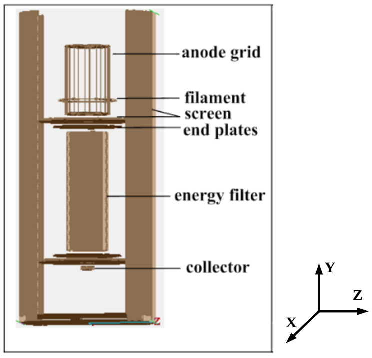


Fig.1. Schematic circuit diagram of AT gauge. Fig.2. The physical model of AT gauge.

3. RESULTS AND DISCUSSION

3.1. Axial symmetric transmission gauge

3.1.1 Modelling and electric field distribution

For analyzing the microcosmic feature of particles in energy filter, the AT gauge structure is modelled and simulated using simion 3D ion optic software. The 3D model, referencing actual parameters of AT gauge, is shown in fig.2. The voltage of filament is 10 V. The potential of anode grid to earth is 110 V. The potential V_{ba} between energy and end-plates is 300V. Energy filter voltage is swept from 30～120 V. The collector voltage is 0 V. The screen and aperture plates are all earthed.

According to the principle of energy filter[7], while the numerical value of kinetic energy of ions within anode and V_{be} are similar, the ions could pass through energy filter and be collected. Due to the electric field distribution and initial position of ions inside of anode space, the kinetic energy of ions distributed differently. Fig.3(b) shows potential variation along X axes on the symmetry XY plane of the anode grid. The curves are the potential distribution near the top, medium, bottom of the anode grid respectively. It could be seen that the potential distributes in 45 V～95 V mainly within anode grid. It means the kinetic energy of gas ions distributes in 45 eV～95 eV or so. If V_{be} is set to be dozens of volts, the gas ions beam with dozens of electronic volts would be collected. ESD ions are stimulated desorption from grid surface on which potential is 110 V. So while the V_{be} is set to be 110 V or so, ESD ions beam could be collected effectively.

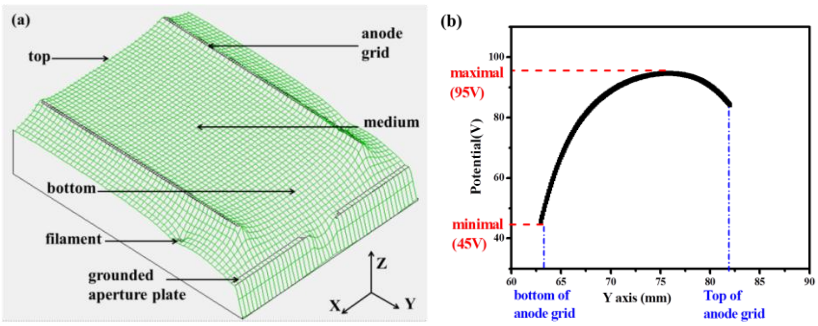


Fig.3. Potential distribution in anode grid. (a) Potential energy contours, (b) Potential variation along Y axis.

3.1.2 Experiment measurement and ions trajectories

The ions current variation, obtained by scanning the voltage V_{be}, is shown in fig.4. It can be seen that there are two peaks while V_{be} equals to 65V and 105V. The two peaks correspond to gas and ESD ions respectively according to principle of filter. That is, when they passed through the aperture plate, the kinetic energy of two kinds of ions are 65 eV and 105 eV respectively. And the energy difference reaches to 40 eV which is large enough to decouple two kinds of ions. it can be seen that, according to ions initial position and kinetic energy distribution, ESD ions could be decoupled from gas ions by choosing optimal V_{be}.

In the simulation, gas and ESD ions are set in gauge and the trajectories are simulated. The variation of ions collection efficiency along with energy filter voltage V_{be} is also analyzed. The simulated trajectories are shown in fig.5 (a). The gas ions beam, which is set randomly inside the anode grid, could be collected effectively while V_{be} is lower. Whereas, ESD ions(briefly H、CO、O) with initial energy 5～7 eV are set on a pole surface of symmetric anode grid. The rings on the top and bottom of the grid are neglected, because the electric field prevents all the ions here to move towards aperture plate. The ESD ions trajectories are shown in fig.5 (b). ESD ions beam would be collected effectively while V_{be} is set to be 105V. The simulated results do not contradict experiments results. Moreover, they also agree well with analysis results of potential distribution shown in fig.6.

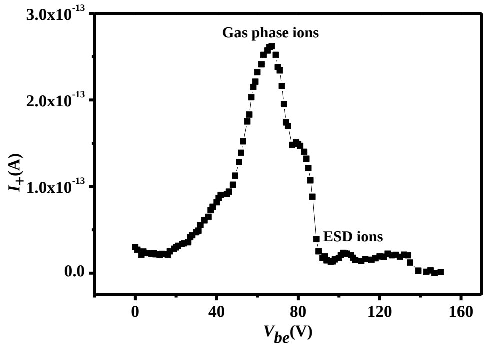


Fig.4 Variation of ions current versus V_{be}

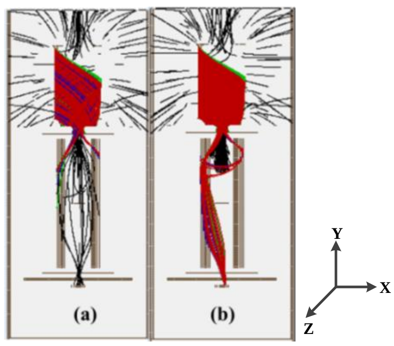
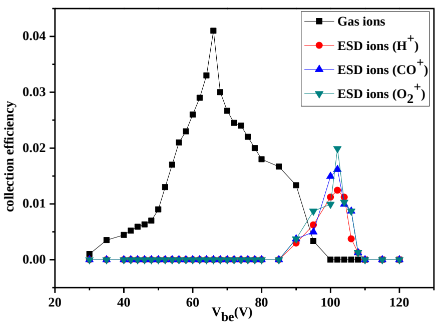


Fig.5. Simulated trajectories in AT gauge.

According to the numerical model shown in fig.5, the energy spectrum of ions is also calculated statistically by sweeping filter voltage V_{be}. Fig.6 shows the variation of ions collection efficiency versus V_{be}. Ions collection efficiency means the ratio between collected ions and total initial ions. The ions collection efficiency varies obviously as the increase of V_{be} from 30 V～120 V. The first peak at V_{be} = 68 V corresponds to the maximum gas ions collection efficiency. While the peak at V_{be} = 106 V corresponds to that of ESD ions. It could be seen too that the maximum collection efficiency is about 4.1% for gas ions and 2% for ESD ions. Our simulated results keep good agreement with that reported by S Watanabe[7]. Numerical and experiment results reported by S Watanabe are 2-3% and 3% respectively.

Numerical work for AT gauge has illustrated the principle of decoupling two kinds of ions with different kinetic energy. The kinetic energy is determined by electric field distribution within anode ionization space. ESD ions could be eliminated by help of energy difference. When energy filter potential V_{be} is optimal, gas ions collection efficiency could reach to maximum. Numerical work keeps a good consistence with experimental results, which also verified that numerical method is correct.



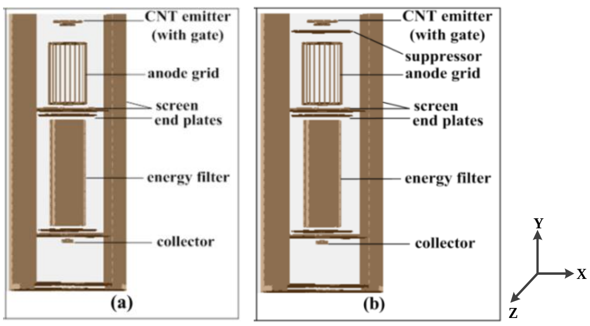


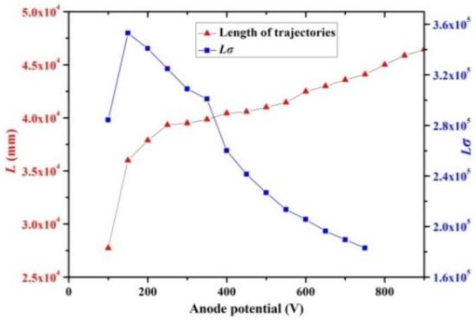
Fig.6. Simulated collection efficiency versus V_{be} in AT gauge. Fig.7. The models of CNT based ionization gauges (a. without suppressor, b. with suppressor).

3.2 CNT based ionization gauge with energy filter

3.2.1 Modelling and optimization

It has been found that the energy filter in AT gauge could decouple ESD ions, based on dozens of energy difference between two kinds of ions. The CNT emitter is used here instead of hot filament in AT gauge to eliminate hot cathode and ESD effect. As is shown in fig.7 (a), the model is constructed. The CNT emitter (Ø5mm) with gate (Ø5mm) is directly placed on top of the anode grid. Distance of CNT and gate is 150 μm. The voltage of CNT emitter is 0 V, and gate voltage is 400 V for a reasonable emission current. In addition, for high sensitivity, the anode voltage is always higher than that of the gate. So the anode voltage is assumed to be 700 V[8].

The potential distribution of the gauge shown in fig.7 (a) is also calculated by the same method described in Section 3.1.1. The potential distribution ranges from 300 V to 600 V within anode grid. So it can be found the kinetic energy difference of gas ions and that of ESD ions (about 300eV) is beneficial for decoupling ESD ions, but it distributed too wide to make the gas ions been collected effectively. So if the anode potential is turned down, energy dispersion could be reduced. Thus a suppressor aiming to decrease the strong electric field penetration effect of gate in ionization space, is placed between gate and anode grid. The new model is shown in fig.7 (b). The voltage of suppressor (outer diameter 20mm and inner diameter 5mm) is set to be 10V. So the energy of electrons passing through the suppressor would be about 10eV. And the electron trajectories in ionization space would vary obviously.



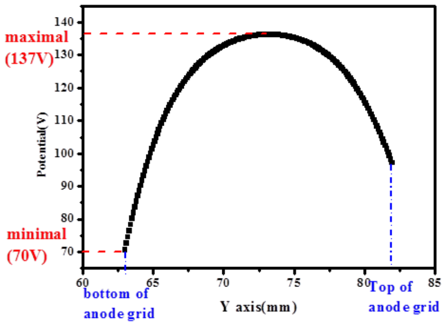


Fig.8. Variation of electrons trajectories versus anode voltage. Fig.9. Potential distribution on symmetric plane of grid in CNT based gauge with suppressor.

As shown in fig.8, influence of anode voltage on length of electron trajectories and ionization cross section is analyzed. As the increase of anode voltage from 100 V to 900 V, The length L would increase dramatically and be stable then. Moreover, the ionization cross section should be considered too. Variation of σ along anode potential is classic bell curve. Take nitrogen for example. σ [220V] /σ [500V] is approximately equal to 1.6[6]. According to the formula (1), in condition of keeping the environment temperature been constant, gauge sensitivity is direct proportion to product of L and σ. It can be seen from fig.8, product $L\sigma$ reaches to maximum peak while anode voltage is set to be about 160 V. Thus for CNT based gauge with suppressor, the anode voltage could be optimized to be 160V or so.

3.2.2 Ions trajectories

According to the optimized results for CNT based gauge with suppressor, potential distribution in ionization space is calculated. As shown in fig.9, the potential distribution of CNT based gauge with suppressor is simulated. The energy of gas ions within anode grid distributed in 70～137 eV, and the energy of ESD ions is 160eV or so, for the potential of anode is 160V. It can be seen, comparing with AT gauge, the CNT based gauge with suppressor has higher energy and wider distribution range for gas ions. Thus, it needs a higher potential V_{be} for energy filter to collect gas ions beam.

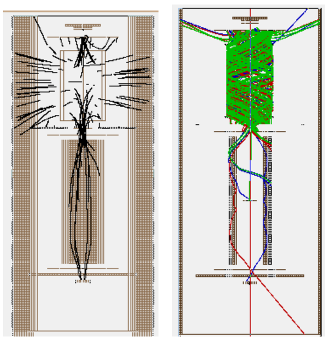


Fig.10. The simulated trajectories of ions in CNT based gauge with suppressor (black-gas ions; blue-H^+; red-CO^+; green-O^+).

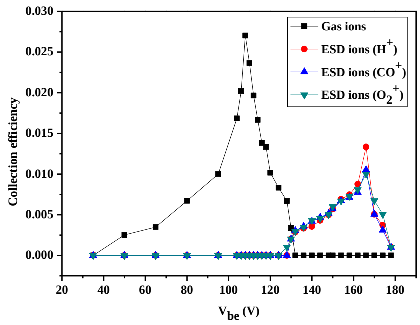


Fig.11. Simulated ions collection efficiency versus V_{be} in CNT based gauge with suppressor

Fig.10 show the variation of ions trajectories in different V_{be}. Thus it can be found, two kinds of ions with different energy could also be collected differently. The gas ions beam with lower energy passed through filter firstly, and then the ESD ions. The calculated results of collection efficiency are shown in fig.11, the peaks of gas ions and ESD ions are at V_{be}=108 V and 166 V, respectively. The energy difference is 58eV or so, which results in higher peak resolution. In addition, the maximum collection efficiency might be about 2.7%, which is lower than that in AT gauge. It depended on the higher distribution energy range 70 eV～137 eV in CNT based gauge with suppressor. Contracting with AT gauge whose distribution energy range 45 eV～95eV, gas ions collection efficiency in CNT based gauge would be little lower.

4. CONCLUSION

A numerical method of calculating electric field and electric particles trajectories, based on ion optic simulation software Simion 3D 8.0, has been proposed in the paper. The numerical results, confirmed by experiment, have illustrated that potential distribution in ionization space affects ions kinetic energy (i.e. energy difference and dispersion), and then influences ions beam to pass through energy filter and be collected. Moreover, considering eliminating hot cathode and ESD effects simultaneously, a CNT based ionization gauge with energy filter model is constructed. Simulation work shows that suppressor reduces the penetration effect of high electric field of gate in ionization space. If the anode voltage is decreased to be 160 V, gas ions kinetic energy would range from 70 eV to 137 eV. While energy filter voltage is optimized to be about 108 V, the maximum collection efficiency for gas ions would be 2.7% or so.

For further optimization and experimental analysis, using this kind of CNT based gauge with energy filter, it is hopeful to extend lower limit of ultra-high vacuum measurement furtherly. There is a potential application in space, high energy physics, high and low temperature environments.

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