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THE ADVANTAGE OF COLD ELECTRON SOURCE IN ELECTRON DIFFRACTION

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Abstract

In this paper, a model for discussing the influence of transverse coherence of electron beams on electron diffraction is established. With reference to Fedele's thermal-wave model, the transverse coherence length is introduced into this model to characterize transverse coherence of electron beams. The simulation results show that transverse coherence of electron beams has a significant influence on the electron diffraction, and the cold electron source with high transverse coherence has an obvious advantage in the electron diffraction.

INTRODUCTION

The diffraction effect of light was first discovered and described by Francesco Grimaldi in 1665. Diffraction has experienced several centuries of discussion and research, the theory of diffraction gradually mature, the application of diffraction is also gradually extensive. Nowadays, with the development of science and technology, electron diffraction has gradually become a hot research field. In materials science, electron diffraction, like X-ray diffraction, can be used for phase identification of crystal and determination of crystal orientation and atomic position. Because electron diffraction is much stronger than the interaction between X-rays and substances, it is especially suitable for structural analysis of samples containing a small number of atoms, such as thin films, particles, and surfaces, in the microscopic analysis of metals and alloys. However, these structure detection techniques are based on electron diffraction imaging theory, and the quality of diffraction imaging is closely related to the quality of the electron source.

As we all know, today, most electron sources in the laboratory or user's hands are obtained by traditional methods, such as field emission or photoelectric emission. In the field of material structure detection and electron diffraction imaging, conventional field emission sources also occupy the mainstream status absolutely. However, the typical effective field temperature of a conventional field emission or photoemission source is about 5000 K. And the transverse coherence length of the electron pulse has a strong relation with the effective temperature: $L_{\perp} = 1/\sqrt{T}$. Therefore, it is obvious that the transverse coherence length of this kind of conventional electron source is very small.

But in recent years, a new type of electron source has been reported [1]. This new type of electron source may solve the problem of low transverse coherence existing in traditional electron sources. It is called Cold Atom Electron Source (CAES) because of its extremely low effective field temperature. The CAES is a source of low temperature electrons or rubidium ions with promising potential as an alternative charged particle source. The CAES works by carefully ionising rubidium atoms trapped in a Magneto Optical Trap (MOT) to generate a low temperature plasma which can then be electrostatically accelerated to form a bunched particle beam. The electron source transverse temperature obtained by this technology can be as small as 10 K or lower.

When we combine the thermal wave model (TWM) [2] with the Kapitza-Dirac effect (KD effect) [3] to calculate the effect of the ponderomotive potential on the transverse coherence of the electron, we find that when the packet or the transverse coherence length is equal to the width of the slit, significant electron diffraction occurs. At the same time, when considering the diffraction of Gaussian beams, it is obvious that if the spot size is much smaller than the size of the slit, it is difficult to obtain the diffraction pattern. Therefore, it can be inferred that, in the detection of material structure, the use of cold electron source to conduct electron diffraction imaging is highly likely to improve the accuracy and authenticity of imaging and retain more diffraction information on the diffraction screen.

In order to discuss the effect of cold electron source on electron diffraction imaging, a simple electron diffraction model was established. Using this model, we analyzed the influence of the transverse coherence length on the contrast and brightness of diffraction fringes.

MODELING I

In order to simulate the electron beam with different transverse coherence temperatures more realistically, we obtain a series of electrons with different coherence temperatures from the H. Luo simulations [4]. Luo used COMSOL to simulate the process of electrons being drawn out by electric field after being trapped by MOT, and obtained a series of electron beams with different parameters. But, in this paper the main focus on the coherence electron beam quality factor is only coherence electron beam temperature. In this design, the electrons have no freedom of rotation and vibration, and we only consider the direction of coherence electron beam transmission, so the coherence electron beam temperature is defined as:

$$T = \frac{mv_{rms}^2}{k}. \tag{1}$$

The electron beam quality is directly affected by the electric field distribution. We change the electric field distribution by changing the electrode structure and position. In the model, in order to find the appropriate electrode structure and related parameters, we can simulate the electron beam quality. According to the initial requirements, we have established two parallel equal-large electrode plates with aperture. Then according to the optimized design, the four pieces design is chosen as the parallel electrode plates. Finally, we got a series of electron beams with

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a pretty low transverse coherence temperature under different parameters setting. The initial design is shown in the Fig. 1 of four electrode plates. Based on this, we give an initial structure of the potential distribution map that was shown in Fig. 2. As shown in Fig. 3, it shows the transverse coherence temperature of electrons at different positions under a certain parameter. Therefore, the parameters of electron beams with different transverse coherence temperatures will be came from this model.

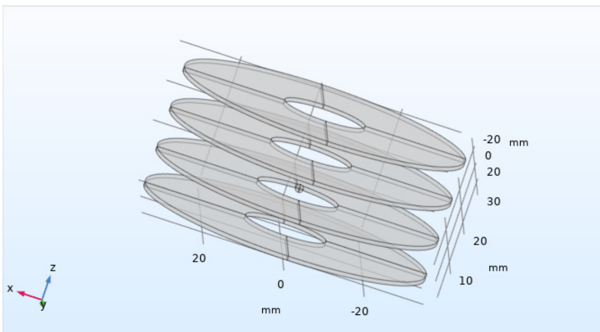

Figure 1: Four electrode plate geometry models.

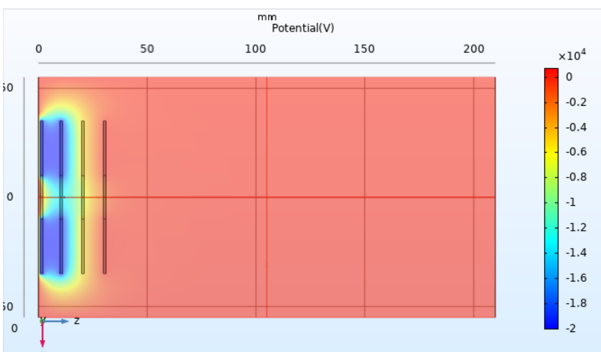

Figure 2: Potential distribution map.

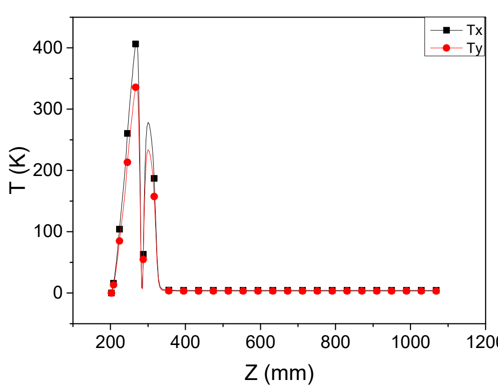

Figure 3: Coherence electron beam temperature.

MODELING II

In the process of analyzing electron diffraction, we mainly consider the volatility of electrons. With reference to Federer's discussion of relativistic charged particle beams, we can approximate the fluctuations of electrons in the diffraction process to Gaussian waves. In R. Fedele's TWM [5], the transverse coherence of the electron beam is introduced as the transverse coherence length into the transverse dynamics model of the electron, so we can use a similar method to discuss the effect of the transverse coherence length or the transverse coherence temperature of the electron beam on diffraction.

Review the single-electron diffraction experiment done by A. Tonomura *et al* [6]. They realized a pure thought two-slit interference experiment. And the interference fringe on the interference pattern is exactly as predicted by quantum theory. The experiment demonstrated the wave-particle duality of electrons. It shows that a single electron can diffract or interfere.

Therefore, in our model, we approximate each electron as a Gaussian wave, and the transverse coherence length of the electron is the full width at half maximum of the electric field. In the simulation of the electron diffraction, because the electron diffraction has the participation of the lens, it belongs to the far-field diffraction, so it can be treated as Fraunhofer diffraction. The one-dimensional Fraunhofer diffraction formula is as follows:

$$E(x)=\frac{\exp(ikz_1)}{i\lambda z_1}\exp\left(\frac{ikx^2}{2z_1}\right)\int_\sigma E(x_1)\exp\left(-\frac{ik}{z_1}xx_1\right)dx_1. \tag{2}$$

Take the electric field of a single electron as the following form:

$$E(x,z)=E_0\frac{w_0}{w(z)}\exp\left(-\frac{x^2}{w(z)^2}\right)\exp\left(i\left[kz-\arctan\frac{z}{z_R}+\frac{kx^2}{2R(z)}\right]\right). \tag{3}$$

Where,

$$w(z_0)=w_0\left(1+\frac{\lambda^2 z_0^2}{\pi^2 w_0^4}\right)^{1/2} \tag{4}$$

$$R(z_0)=z_0\left(1+\frac{\pi^2 w_0^4}{\lambda^2 z_0^2}\right) \tag{5}$$

$$z_R=\frac{\pi w_0^2}{\lambda}. \tag{6}$$

When $z=z_0$,

$$\mathrm{E}(x_1)=\mathrm{E}(x_1,z_0). \tag{7}$$

And the transverse coherence length of electrons is proportional to $1/|k_x|$ and $k_x=2\pi/\lambda_x$. In this article, only qualitative analysis is needed. So Eq. (8) can be substituted into Eq. (2)

$$w_0\sim\sigma_\perp\sim 1/|k_x|\,. \tag{8}$$

Then, three sets of electron beams with different coherence temperatures are used as the light source from Model I, $\lambda_z=h/(m_e v_z)$. z_0、 z_1 are equal to 0.001 m and 0.5 m, respectively. The slit is selected as a double slit with width of 10 nm and spacing of 20 nm. The electron diffraction patterns at different coherence temperatures are obtained by numerical integration of Eq. (2), as shown in Fig. 4.

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DISCUSSION

There are four pictures in Fig. 4. Figure 4 (a) shows a Frunhofer double slit diffraction pattern of an ideal Gaussian wave. In Fig. 4 (b), (c) and (d), there are three double slit diffraction fringes of electron waves at different transverse coherence temperatures. It is obvious that when electron waves are at a low transverse temperature, the fringe is clear and closer to the ideal condition. When the transverse coherence temperature of the electron waves rises to 400 K, diffraction information is gradually lost. Also, the intensity of diffraction is decreases as the transverse coherence temperature increases.

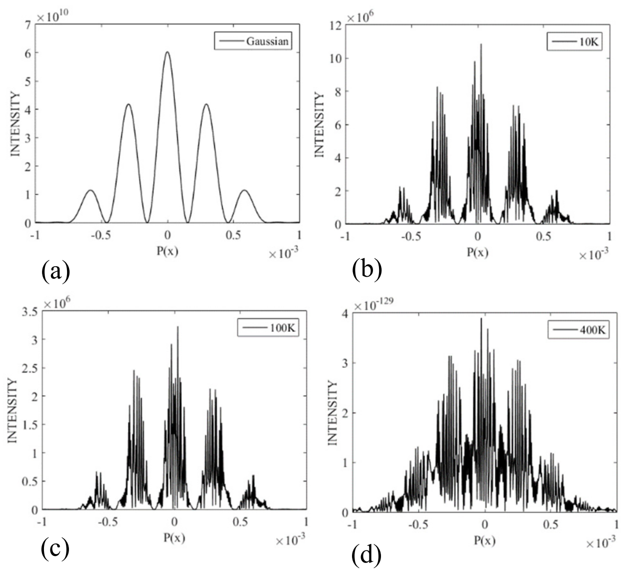

Figure 4: The x-axis is the coordinate of diffraction plane, y-axis is the diffracted intensity. (a) Diffraction of an ideal Gaussian wave; (b) Diffraction of the electron beam with a temperature of 10 K; (c) Diffraction of the electron beam with a temperature of 100 K; (d) Diffraction of the electron beam with a temperature of 400 K.

CONCLUSION

This simple model qualitatively demonstrates the influences of the transverse coherence temperature or the transverse coherence length of the electron source on the diffraction fringes. The diffraction results basically agree with the diffraction theory. The results also show the advantages of cold electron source in electron diffraction. Cold electron sources with a low transverse coherence temperature or a long transverse coherence length can reduce the loss of structural information and improve the brightness during diffraction imaging.

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