Emission Property of Sc_2O_3-W Matrix Cathode and Generation of High Current Density Sheet Beams for THz Vacuum Electron Sources

Jinshu Wang *, Wei Liu, Yiman Wang, Meiling Zhou, Tieyong Zuo
The Key Lab of Advanced Functional Materials, Ministry of Education China, School of Materials Science and Engineering, Beijing University of Technology, Beijing 100022, China
* E-mail: wangjsh@bjut.edu.cn

(Received 30 August 2010; accepted 26 January 2011)

Abstract: Sc_2O_3 doped tungsten matrix dispenser cathode prepared by liquid-liquid doping method exhibits high emission property, i.e., space charge limited current density reaches 48 A/cm^2 at 850 ^oC_b together with the slope of 1.44 has been obtained. Scanning electron microscope observation shows that the matrix has sub-micrometer microstructure, which is favorable for the diffusion of active substance from the inner part of cathode to the cathode surface. A multi-layer of active substance of Ba, Sc, O formed on the surface of the cathode leads to its conspicuous emission performance. Based on this kind of cathode, rectangular electron beam of 100 $\mu m \times 600$ μm and square beam of 600 $\mu m \times 600$ μm have been obtained. A uniformly distributed space charge limited current density of more than 50 A/cm^2 can be drawn out from the emitting area at 950 ^oC_b and keeps stable for at least several hundred hours.

Keywords: Scandia doped tungsten, cathode, emission property, shaped beam

doi: 10.11906/TST.050-058.2011.06.07

1. Introduction

Terahertz (THz) has been aroused more and more attentions around the whole world due to the numerous present and future applications in the fields such as time-domain spectroscopy, biomedical, security, imaginings, and ultrahigh speed electronics. Among all the methods for producing Terahertz radiation, vacuum electronics is considered as one of the most promising way due to their compact structure, relative higher output power of the terahertz vacuum electron devices. THz vacuum electron devices place intense demands on cathode current density capability because it is necessary to reduce the cathode area to minimize convergence when generating the required sheet electron beams, which have the current densities of 50-100 A/cm^2, high transverse aspect ratios, and dimensions of a few hundreds micrometers. Current widely-used Ba-W or M type cathodes have difficulties in meeting these requirements as they normally are limited to a current density of 10-20 A/cm^2 at an operating temperature low enough to give acceptable life. It was found that impregnated scandate cathode, in which scandia was added to the barium calcium aluminates impregnants, has exhibited much higher emission property than Barium-tungsten cathode, is considered as the next generation high emission cathodes.

The research on scandate cathodes have sustained a continuous advance since the end of 1970s[1-8]. A common problem referring to emission non-uniformity exists in all kinds of scandate cathodes. The non-uniform emission could mainly be attributed to the uneven distribution of scandia or scandium which played an important role in the improvement of cathode emission. Our work on the improvement on the performance of scandate cathodes started in 1999 and still continue today[9-12]. The research is aimed at the development of a scandate cathode with a scandia mixed tungsten matrix having sub-micron structure since it is believed that such structure is favorable for the diffusion of active substance to the surface to obtain the high emission property. The microstructure and emission property of the cathode will be introduced.

High current shaped beam electron source has attracted great attention for its possible application in THz vacuum electron devices like Backward Wave Oscillator [13] and other devices, since direct generation of sheet beam from cathode has the advantage of simplifying the focus system so as to compact the devices. Generation of shaped beam from scandate cathode with a scandia mixed tungsten matrix also has been investigated in this work.

2. Experimental Methods

The fabrication process and characteristics of scandia doped matrix scandate cathode have been described in previous work[9,10]. In brief, high mixing quality of Sc_2O_3 doped W matrices (Sc–W matrices for short in this paper) was obtained by using Sc_2O_3 doped W powders produced by liquid–liquid doping (Sol–gel) technique[10] and carefully controlled pressing and sintering procedures. The $4BaO.1Al_2O_3.1CaO$ was impregnated into Sc–W matrices with porosities of about 26–28%. After impregnation, the residue on the surfaces of cathodes was removed by ultrasonic water cleaning instead of mechanical polishing.

Emission properties of the cathodes were tested in close-spaced diode configuration in either an Ultra High Vacuum system with a Mo-anode or in sealed testing tubes with a water-cooled copper anode by a computer-controlled automatic emission-testing apparatus.

3. Results and Discussion

3.1 Emission Property

The cathode was activated at 1150 $°C_b$ for about 3h before measurement. Fig. 1 shows typical I-V plots together with related slopes at temperatures from 750 $°C_b$ to 900$°C_b$ with a pulse width of 5 μs and a 100 *Hz* repetition frequency. During the measurement, 3 *mm* diameter cathodes were mounted into Mo sleeves and set in front of a degassed Mo anode with an adjustable spacing. The anode was moved away from cathode during activation to lower the contamination by evaporants from the cathode and was normally kept at a distance of 0.5*mm* from the cathode during emission testing to minimize the effect of edge emission, which is usual in cathode research. It could be seen from Fig.1, the electron emission current density of this cathode could get to 48.8 A/cm^2 at 850^oC with the slope of 1.44 which could be used to demonstrate the emission uniformity of the cathode. The more close to the ideal slope of 1.5, the more uniform the emission current density. No obvious current degradation was observed on the I-V curves as the duty cycle varied from 0.1% to 2.5% with pulse widths from 10 to 250μs. By extrapolating zero field current density under different temperatures according to Richardson equation shown in equation (1), the parameters of the Richardson equation of this impregnated cathode were calculated.

$$\lg(\frac{J_0}{T^2}) = (\lg A - 5040a) - 5040\phi_0(\frac{1}{T}) \quad (1)$$

Where, Jo was zero field current density and T was the temperature. The low work function Φ_0 was as low as 1.14 *eV*, with Richardson constant A of 6-7$Acm^{-2}K^{-2}$, indicating that this kind of cathode had good emission property. The emission capability is at the same level as that of laser ablation deposition scandate cathode, if the so-called 10% method is applied for emission evaluation [4].

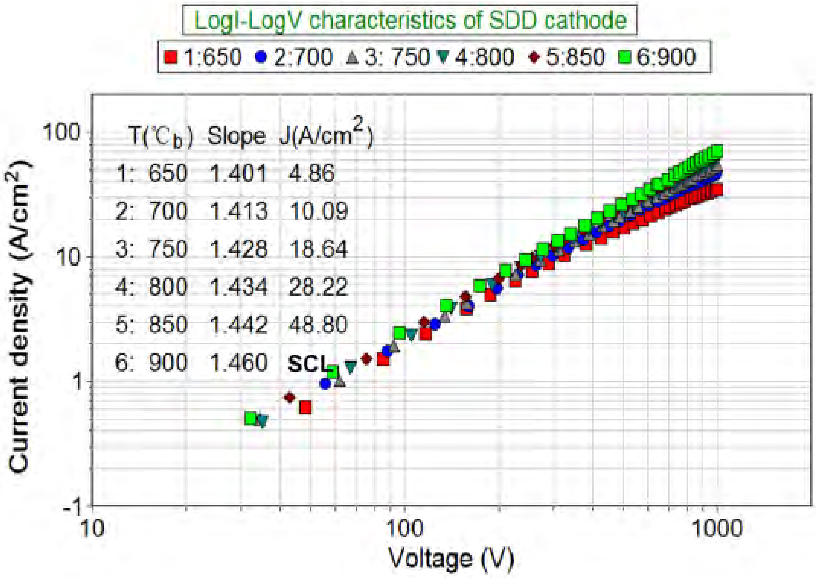


Fig.1 Emission capability of Sc_2O_3 doped W matrix cathode.

In order to find out the emission stability of this cathode, a life test was carried out with a continuously pulsed loading of 70 A/cm^2 at 950°C_b. After the cathode had operated for 526 hours under the above conditions, the current density kept almost stable, as shown in Fig.2. R.E.Thomas et al reported that as for ordinary Ba-W cathode, it could operate 50*h* under the condition of 45A/cm^2 at 1373°*C*[14]. Therefore, Sc_2O_3-W matrix impregnated cathode could provide the lifetime about 10 times longer with a continuously pulsed loading of current density about 1/3 times higher at a temperature about 300-400°*C* lower than Ba-W cathode.

These results demonstrated that this kind of cathode was able to provide the highest current density together with proved emission uniformity and good reproducibility compared with currently used impregnated scandate cathodes.

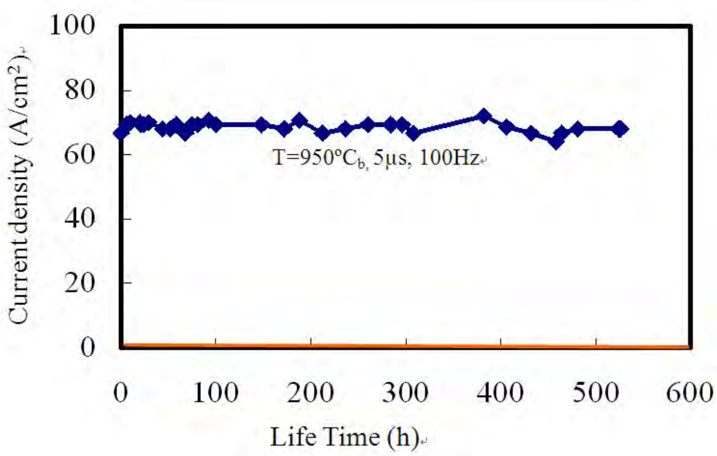
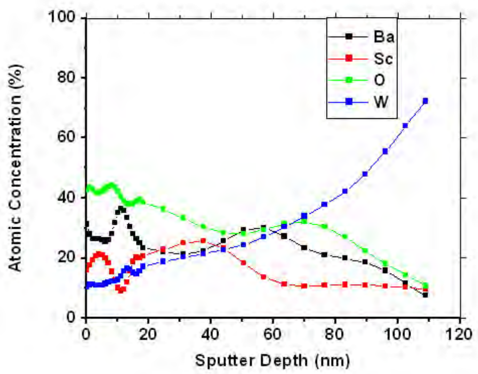


Fig. 2 Life curve of 70A/cm^2 loading at 950°*C*.

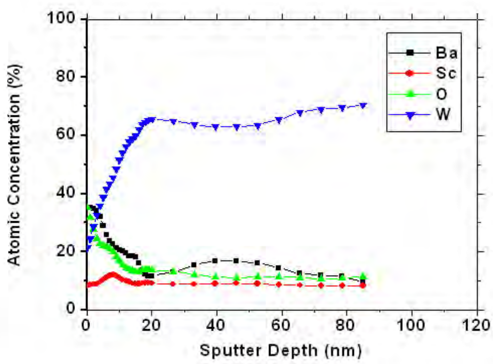
In order to get the understanding of the surface layer of active substance of Ba, Sc, O and the role of the surface layer in the emission, depth profiles of Ba, Sc, O on W grains of a fully activated cathode and that after life test, were obtained using a PHI 700 Auger microprobe with an electron beam of 10 *kV*, and ion beam of 500-1000 *eV* rastered over an area of 3*mm* ×3*mm*. The atomic concentrations of the elements were calculated by the following equation (2).

$$C_{X_I} = \frac{\frac{I_i}{S_i}}{\sum_{j=1}^{n} \frac{I_j}{S_j}} \tag{2}$$

Where, I_i is the peak to peak height of the element, and S_i is sensitivity factor of the relative element. Fig.3 illustrates the depth profiles taken from the Sc_2O_3-W matrix cathode (a) and the cathode after 526*h* life test (b). It was clear that Ba, Sc and O covered the W substrate in thickness of about 80 *nm*, with Ba:Sc:O concentration ratios of about 2.0:1:2.7 at the outermost surface, as shown in Fig.3a. After life test, the thickness of the surface layer decreased to about 20 *nm* and the content of Sc decreased with the change of Ba:Sc:O concentration ratios at the outermost surface to 2.6:1:4.2. It was reported that the thickness of the monolayer of the M-type cathode was about 10 *nm*[14], therefore, a Ba-Sc-O multilayer having certain ratios of Ba:Sc:O was formed at the surface of Sc_2O_3-W matrix cathode after activation, which was considered to be responsible for copious emission capability. Both the decrease of the thickness of active surface layer and the decrease of the content of Sc could lead to the degradation of current density.



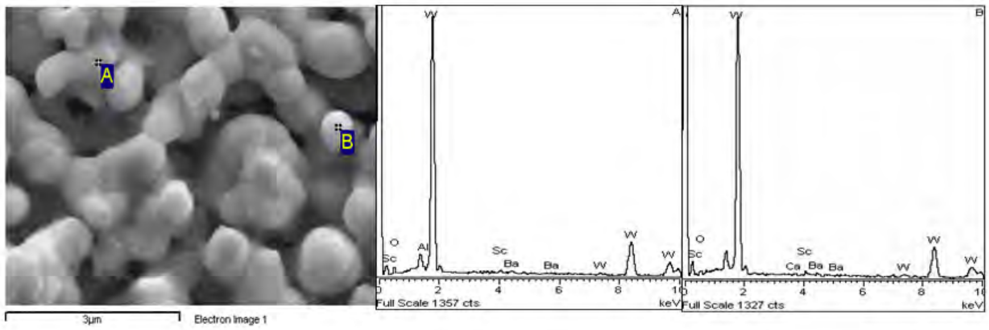
(a)



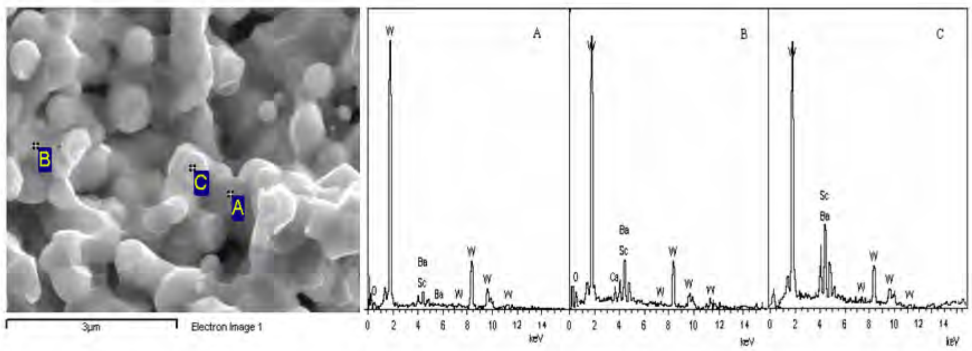
(b)

Fig. 3 Depth profiles of elements on the surface of Sc_2O_3-W fully activated cathode (a) and depth profiles of elements on surface of the cathode after life test (b).

Fig. 4 shows the surface microstructure and fracture microstructure together with related EDAX of Sc_2O_3-W matrix cathode after water cleaning. It could be seen that the cathode composed of sub-micron quasi-spherical tungsten grains and lots of pores. These pores were formed during the sintering process. In the initial period of sintering, new linking areas (sintering neck) among particles were formed. These sintering necks grew with time and blocked the grooves among the linking pores, so the individual pores were formed. As for the impregnated cathode, a certain amount of pores is indispensable for the matrix to meet the requirement of Ba,Ca aluminate impregnating. Furthermore, these pores could provide corridors for the active substances to diffuse from the inner part to the surface during cathode activation and operation periods. Figs.4b and d display that the impregnants composed of elements of Ba, Sc, O, Ca existed in the pores. Spherical tungsten grains had low surface energy, so the growth of tungsten grain could be hampered to a certain extent during activation and operation periods, and thus the sub-micrometer microstructure could be kept. Therefore, sub-micrometer microstructure of matrices with quasi-spherical tungsten grain shape played a dominate role in emission capability improvement of such cathodes.



(a) (b)

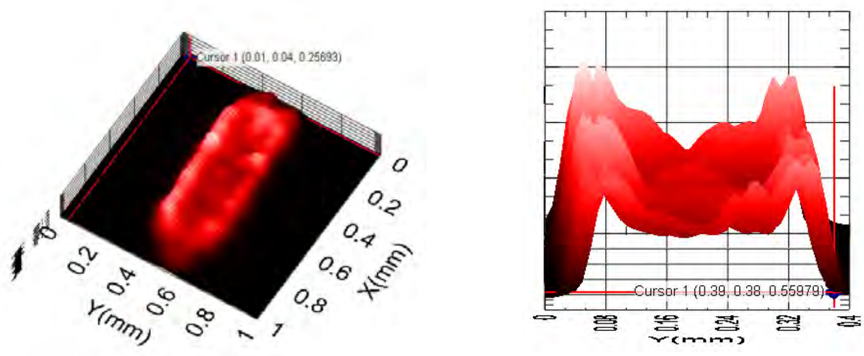


(b) (d)

Fig. 4 Microstructure of Sc_2O_3 doped W matrix cathode. (a) Surface morphology, (b) EDAX result of (a), (c) Fracture morphology, (d) EDAX result of (c).

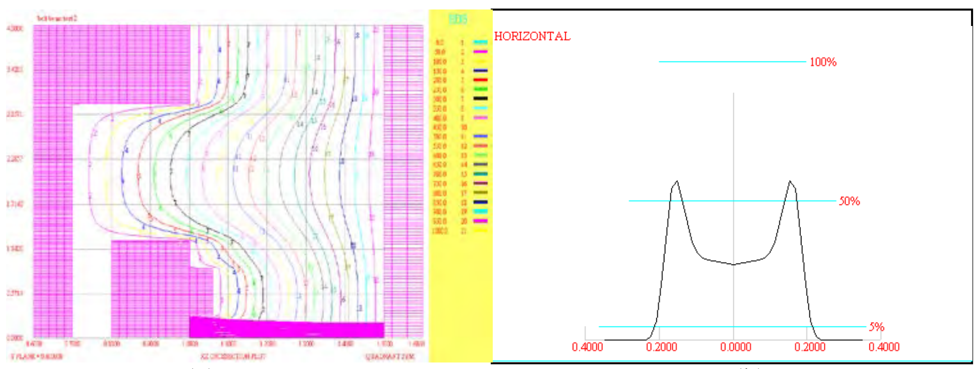
3.2 Shaped Beam Generation

For the micro-fabricated Terahertz (THz) vacuum electron devices, a high current density sheet beam source is a crucial component among the challenging technologies that must be mastered to enable the realization. Sheet beams can be obtained from normal cylindrical cathodes by means of specially designed compression systems. However, direct generation of sheet beams from cathodes, which are capable of providing sufficiently high current densities, has the advantages of simplifying the focus optics which makes the devices more compact and facilitates the formation of high-quality, high aspect–ratio electron beams. Direct generation of sheet beams from these cathodes thus becomes the most promising approach to meet the requirements for advanced vacuum electron devices like THz sources. The shaped electron beam like rectangular or square beams in dimension of several hundreds of micrometers had been developed based on Sc_2O_3-W matrix cathode. The cathode had an electron emitting area in a special shape, which was surrounded by non-emitting surface, so that it could provide a shaped electron beam. Fig. 5a shows the outline of rectangular electron beam. It showed that the emission area had rectangular shape with the size of 200 $\mu m \times 800$ μm, which was consistent with our original design. It also showed that the emission current density distributed uniformly in the center but much lower than that in the edge, in other words, edge emission was very strong, as shown in Fig. 5b. CAD simulation had been applied for the simulation of the distribution of electronic field and electron movement orbits to find out the reason for the edge emission. Fig. 6 shows the simulation results of electronic field caused by the space charge distribution during the electron emission by using EBS5.0 simulation software. The simulation result shown in Fig. 6b was consistent with the measurement result illustrated in Fig. 5b. The electron fields accumulated at the edge of shape beam when the non-emitting layer thickness was large, leading to the higher emission current at the edge. Therefore, decreasing the thickness of the non-emission layer or changing the beam shape might improve the distortion of edge electron field.



(a) (b)

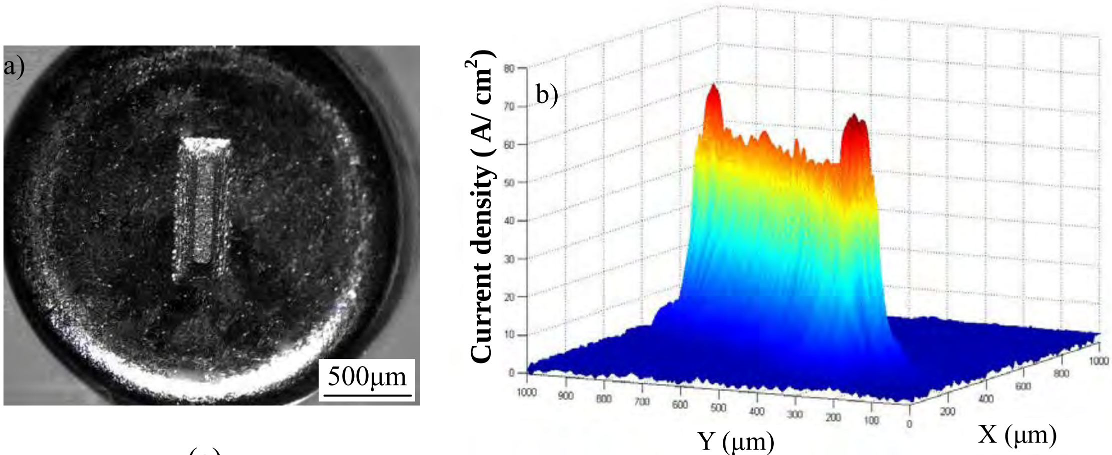
Fig.5 (a) Rectangular electron beam with the size of 200 $\mu m \times 800$ μm and (b) distribution of emission current density.



(a) (b)

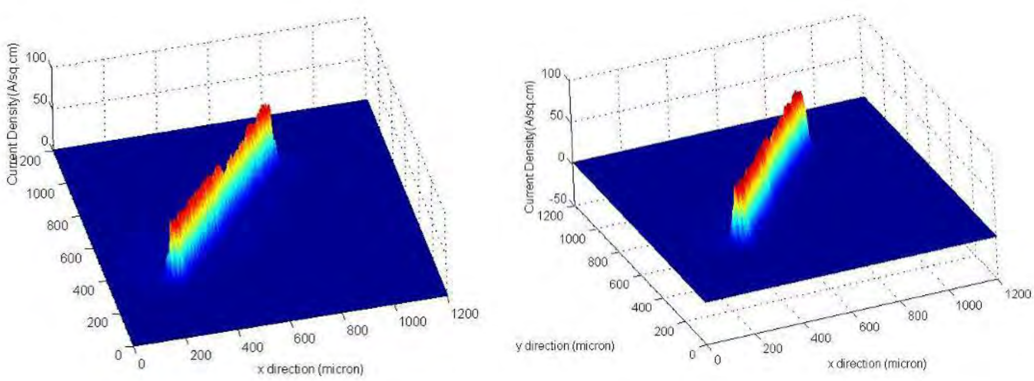
Fig. 6 Simulation results for the shaped beam shown in Fig.5. (a) Electron field, (b) Section of electron beam.

Fig. 7 shows the micrograph of emission area and electron emission current density of rectangular beam of 600 $\mu m \times 100$ μm with the space charge limited current density of over 60 A/cm^2. The local current densities from areas of 5μm in diameter had been measured and used to evaluate the beam current density. By covering the cathode with a antiemission mask possessing special shape, a proper thickness and proper angel (Fig.7a), the desired high current density electron beam had been obtained. As shown in Fig.7b, the electron beam exhibited a regular rectangular shape of 600 $\mu m\times100$ μm with a distinct boundary between the emission area and non-emission area. Life test was performed for the sheet beam at a cathode operating temperature of around 950^oC with continuous pulsed loading of above 50 A/cm^2. Fig.8 illustrates the cross section of shaped beam measured at 70 *h* and 500 *h* during the life test. As shown in Fig.8, the sheet beam had regular shape of 600 $\mu m\times100$ μm and no emission was found in the surrounding area after operating for 70 *h* (Fig.8a) and kept stable even after operating for 500 *h* (Fig.8b), indicating that the antiemission mask could hamper the emission from the cathode and no electrons were emitted from the surface of antiemission mask, since we worried that active substance like barium and oxygen might diffuse through the anti-emission mask onto the surface of this mask so as to cause unexpected emission from the surrounding areas during cathode operation. In addition, the current density of the electron beam was checked at intervals and the results are illustrated in Fig.9. It is clear to see that both beam shape and current density remained stable for more than 500 *h*. The local current densities from areas of 5μm in diameter had been measured and used to evaluate the beam current density. I-V curves drawn from different spots of the emission area indicate that over the entire cross section of the beam, the cathode operated in the space charge limited region during the life test.



(a) (b)

Fig. 7 Picture of the cathode with an emission area of 600 $\mu m\times100$ μm (a) and distribution of emission current density of the cathode(b).



(a) (b)

Fig. 8 Variation of beam shape measured at operating for 70 *h* (a) and 500 *h* (b).

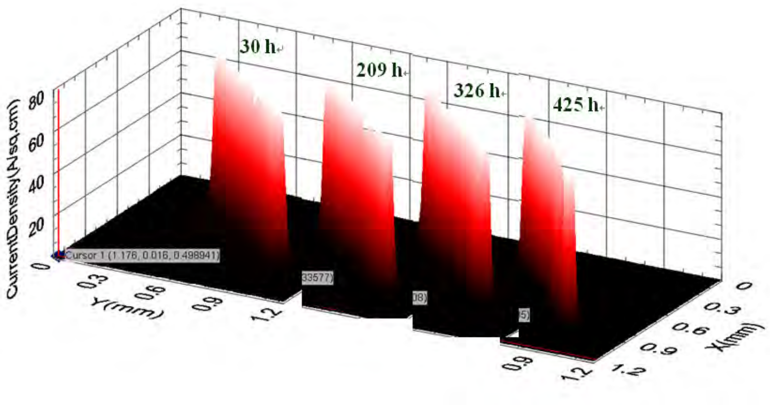


Fig.9 Measured beam profile from a cathode during operation period at 950^oC_b.

4. Conclusions

1) Scandia doped porous tungsten matrix cathode with a sub-micron matrix composed of quasi-spherical W particles and uniform distribution of active substance of Ba, Sc and O had been prepared by liquid-liquid doping method.

2) Scandia doped tungsten matrix cathode had excellent emission property. J_{div} of 48 A/cm^2 at 850 ℃$_b$ with the slope of 1.44 was obtained.

3) The lifetime performance of the cathode shows that the cathode could provide stable emission with a continuously pulsed loading of 70 A/cm^2 at 950°C_b.

4) Shaped electron beams like rectangular beams in dimension of several hundreds of micrometers had been developed based on this kind of cathode. The beam kept stable for more than 500 *h* with continuous pulsed loading of above 50A/cm^2.

Acknowledgement

This work is sponsored by National Nature Science Foundation of China 51071005, Beijing Natural Science Foundation 2102007, Program for Excellent Talents in Beijing PHR201006101, Doctoral Fund of Ministry of Education of China 20101103110018.

References

[1] A.Oostrom and L. Augustus, "Activation and early life of a pressed barium scandate cathode". *Appl. Surf. Sci*., 2, 173-186, (1979).

[2] J. W.Ginson, G. A. Hass, and R. E. Thomas, "Investigation of scandate cathodes:Emission, fabrication, and activation processes", *IEEE Trans. Electron Dev*. ,36(1) ,209-214, (1989).

[3] S. Yamamoto, S. Taguchi, I. Watanaba, and S. Kawase, "Electron emission properties and surface atom behavior of an impregnated cathode coated with tungsten thin film containing Sc_2O_3", *Jpn. J. Appl. Phys*., 25(7), 971-975, (1986).

[4] J. Hasker, J. Van Esdonk and J. E. Crombeen, "Properties and manufacture of top-layer scandate cathodes", ,*Appl. Surf. Sci.,*26, 173-195, (1986).

[5] J. Hasker, J. E. Crombeen, P. A.M. Dorst, "Comment on progress in scandate cathodes", *IEEE Trans. Electron Dev*., 36(1) ,215-219, (1989).

[6] S.Sasaki, T. Yaguchi, Y. Nonaka, S. Taguchi, M. Shibata, Surfce coating influence on scandate cathode performance, *Appl. Surf. Sci.* ,195, 214-221, (2002).

[7] G. Gäertner, P. Geittner, H. Lydtin, et al. "Emission properties of top-layer scandate cathodes prepared by LAD", *Appl.Surf. Sci*.,111,11-17, (1997).

[8] A. Shih A, J. E. Yater , C. Hor, "Ba and BaO on W and on Sc_2O_3 coated W", *Appl. Surf. Sci*., 24,535-54, (2005).

[9] J. Wang, W. Liu, Y. Wang, L. Li, Y. Wang, M. Zhou, "Sc_2O_3–W matrix impregnated cathode with spherical grains". *J. Phys. & Chem. Solid.,* 69 (8), 2103-2108, (2008).

[10] J. Wang, Y. Wang, W. Liu, L. Li, Y. Wang, M, Zhou, "Emission property of scandia and Re doped tungsten matrix dispenser cathode". *J. Alloy. & Comp*., 459 (1-2), 302-306, (2008).

[11] J. Wang, W. Liu, L. Li, Y. Wang, Y. Wang, M. Zhou, "A study of scandia-doped pressed cathodes". *IEEE Trans. Electron. Dev*., 56 (5) ,799-804, (2009).

[12] J. Wang, W. liu, M. Zhou, Y. Wang, H. Li, T. Zuo, "Method of manufacturing a pressed scandate dispenser cathode", US patent, US 7722 804 132, (2007).

[13] M.Shin, J.K.So, K.H. Jang, J.H. Won, J. I. Kim, A. Srivastava, and G.S. Park, "Superradiant Terahertz Smith-Purcell Radiation from Surface Plasmon Excited by Counterstreaming Electron Beams". *Appl. Phys. Lett.*, 90(3), 031502, (2007).

[14] R.E.Thomas, J. W. Gibson, G. A. Hass, and R.H.Abrams, "Thermionic Sources for High-Brightness Electron. Beams", *IEEE Trans. Electron Dev.*, 37(3) 850-861, (1990).