Invited Paper

Scandia-added Tungsten Dispenser Cathode Fabrication for THz Vacuum Integrated Power Amplifiers

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Abstract: The *sine quo non* of terahertz (THz) vacuum electron beam devices is a high current density thermionic cathode, the development of which has been a major focus of our efforts. As a specific application, we have fabricated a high current density, long life scandate dispenser cathode to develop a 220 *GHz* sheet beam electron gun for a high power traveling wave tube (TWT) amplifier for the DARPA High Frequency Integrated Vacuum Electronics (HiFIVE) program. Using the solution-gellation (sol-gel) method, Sc_2O_3-added tungsten powders were made for use in high current density thermionic cathodes. The particle size of the powders was uniform, spanning the range from nanometers to micrometers, and was controllable by adjusting the sol-gel processing parameters. The densified cathode matrix fabricated from the powders has high porosity, uniform grain size and scandia dispersion, and open pore distribution.

By using the Mori Seiki NN1000 nano-CNC (developed by DTL, Davis CA), high current density nano- and micro-composite scandate dispenser cathodes were machined with high precision resulting in good surface smoothness, tight tolerance, and sharp edges. Sc_2O_3-added tungsten dispenser cathodes were tested in both UHV cubes employing a closely-spaced diode (CSD) configuration under pulse mode and in Cathode Life Test Vehicles (CLTV) with a Pierce gun configuration under CW mode. Space charge limited current densities of 38 A/cm^2 at $915^oC_{\rm br}$, and 80 A/cm^2 at $1050^oC_{\rm br}$ were obtained by using Sc_2O_3-added (3.56 *wt*.%) tungsten powders. The cathode was sintered at 1700^oC by using a batch of Sc_2O_3-W powder with an initial particle size of 700 *nm* yielding cathode pellets strong enough for machining. In CLTV #1, owing to a perveance issue (there is a 100 *micron* gap between the focus electrode and cathode emission surface), 10 A/cm^2 dc current density can be achieved at practical temperature of $1120^oC_{\rm br}$ for more than 2000 *hours*. In CLTV #2 with a reduced focus electrode gap (30 μm), 45 A/cm^2 dc current density has been obtained. The collector pulse current density with 56 A/cm^2 at $960^oC_{\rm br}$ at 4 *kV*, and up to 104 A/cm^2 at $1040^oC_{\rm br}$ was obtained in the CLTV #3 gun with a cathode out of 70 *microns* beyond electron focus. This CLTV will be under CW life testing with 40 A/cm^2 current density which is the design value for the 220 *GHz* sheet beam TWT.

Keywords: Scandate cathodes, High current density, CLTV (Cathode Life Test Vehicle), Nano CNC machining.

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1. Introduction

Cathodes are used as electron sources in a wide variety of vacuum devices. The cathode is the performance limiting component in high frequency linear beam amplifiers such as traveling wave tubes and klystrons. For any type of cathode, a difficult problem is controlling the work function uniformity of the emitting surface. Typically, in the tungsten-based modern dispenser cathode, the porous tungsten pellets are produced by pressing tungsten powder and sintering the pellets in a high temperature furnace at over 2000°*C*. The porosity of the tungsten pellets can be controlled by the initial particle size, shape, and uniformity of the tungsten powder. However, typical commercial tungsten particles have an average diameter of 4-5 *microns* with a wide distribution between submicron and more than 10 *micron* size and are irregularly shaped. As a result, there is no precise control of the porosity of most cathodes made by using micron size tungsten powder with resultant loss of direct control on the uniformity and amount of refractory barium calcium aluminate compositions that are impregnated and diffused into the porous regions of the tungsten matrix. Several techniques have been used to improve the quality of commercial tungsten powders [1-3] with specific attention given to control of particle size, distribution, and morphology, all of which are major factors determining the cathode performance.

For the development of vacuum electron devices (VEDs), especially for high power amplifiers at frequencies ranging from 30 *GHz* to 1000 *GHz*, the cathodes are required to provide high current density (up to 100 A/cm^2). However, the conventional thermionic cathode technology falls short of that current density by about a factor of 5 or greater [4-6]. Because of its low work function, a scandate cathode can provide a high emission current density at a low operating temperature. Scandate cathodes offer a way to increase emission from current limits of 10 A/cm^2 to about 100 A/cm^2 [7-10], and even higher [11]. The quality of the tungsten matrix and uniformity of scandium distribution are of the utmost importance for the uniformity and density of the emission. To provide the required advances in cathode technology for THz VEDs, the University of California Davis (UCD) and Beijing Vacuum Electronics Research Institute (BVERI) have been collaborating on the basic science. In the UCD/BVERI collaboration, the developmental efforts on scandate cathodes have concentrated on improving uniformity in the emission and robustness in the performance. We adapted and developed the sol-gel technique to produce the Sc_2O_3-added tungsten powders with spherical shape and uniform controllable particle size ranging from nanometers to micrometers. As a specific application for the DARPA High Frequency Integrated Vacuum Electronics (HiFIVE) program [12], the team developed a very high current density cathode employed to form a well confined, 25:1 aspect ratio sheet beam having a current density of 750 A/cm^2.

Compared with other types of scandate cathodes such as mixed-matrix scandate cathodes [13], impregnated scandate cathodes [5], and top-layer scandate cathodes fabricated by thin-film technologies [14-15], the Sc_2O_3-added tungsten dispenser cathodes made by our sol-gel technique have important advantages including [9-10]: (1) uniform nanometer size tungsten particle distribution with uniform nanometer size Scandia dispersion; (2) rapidly sintered cathode matrix with uniform nanosize grains and high open nano pore distribution; (3) high capacity of active substances with uniform distribution; (4) a uniform layering of Ba, Sc, and O on tungsten grains after activation to improve the emission capability and uniformity of these cathodes; and (5) controllable fabrication process with good reproducibility.

Here, we report results of sol-gel synthesis of both nanosize and microsize Sc_2O_3-added tungsten powders with controllable uniform particle sizes that are well-suited for use in high current density thermionic cathodes. By judicious control over sintering conditions, these powders were densified into nanostructured and microstructured Sc_2O_3-added tungsten matrices with uniform tungsten grains and homogenous pore distribution. The cathodes machined and tested in closely-spaced diodes (CSD) with the pulse mode revealed very high current density. Nanocomposite Sc_2O_3-doped tungsten dispenser cathodes were also tested in Cathode Life Test Vehicles (CLTV) with a Pierce gun configuration under CW mode.

2. Sc_2O_3-added tungsten dispenser cathode fabrication

2.1 Cathode matrix preparation

Techniques for fabricating porous cathode matrices require close control of powder particle size, particle-size distribution, particle shape and purity of the powder, as well as sintering temperature and compaction pressure. One of the factors, which largely influences the quality of the tungsten matrix, is the starting tungsten powder. The quality of the tungsten matrix was improved by using graded commercial tungsten powder [1]. The shape and particle distribution of the tungsten powder will affect the distribution and densities of pores and specific areas of the matrix. The porous tungsten matrix with uniform pores is the foundation of a cathode to obtain uniform electron emission and high current density. Since the Ba-Sc-O layer formed on the tungsten substrate is responsible for the high emission density, the uniformity of the monolayer coverage will be essential to the uniformity of the electron emission [16-19]. Different particle size Sc_2O_3-added tungsten powders have been made using the sol-gel method, including ~72 nm, 146 *nm*, 272 *nm*, 587 *nm*, and even micron size 1-2 μm [10][20]. These powder particles are very uniform and have spherical shape with high purity, leading to a very uniform high porosity after sintering and precise control of the porosity of the cathodes. By this sol-gel method, the scandium can be uniformly dispersed through the tungsten body and/or the cathode surface.

Typical commercial tungsten powder with a wide size distribution and irregularly shaped with large agglomerations may require additional operations, such as powder grinding, sieving to get rid of the agglomerate particles and fine powders, or hydrogen firing before use. The powders made by the sol-gel method and followed by hydrogen reductions, can be directly pressed into pellets.

The Sc_2O_3-added tungsten powder with small nano size need be sintered at very low temperature, less than 1200^oC for a porous matrix with 25% porosity. The cathode matrix after this low sintering temperature is quite fragile causing considerable problems for future machining and engineering. Both the 500-700 *nm* and 1-2 μm powders were chosen for current applications. The Sc_2O_3-added tungsten powders were die-pressed into porous matrices at a pressure of 2.0 $ton{\cdot}cm^{-2}$. Figure 1 shows the surface of the cathode matrix sintered at 1700^oC by using 500-700 *nm* material for 20 *min* under a hydrogen atmosphere. The porosity of the sintered matrices was measured by a mercury intrusion-method (Micromeritics AutoPore IV 9500). The porosity of cathode matrix is a major controlling parameter in the dispenser cathodes industry defined by open pores, pore size, and pore distribution. The average pore diameter of this nano composite matrix is 212 *nm*. This nanometer pore size is 10 *times* smaller than that of normal matrices made from 4-6 μm tungsten particles, which have pore diameters in the range of 1.5-2 μm [21]. The bulk porosity of the sintered pellets is 28.2% and the average grain size of the matrix is ~800 *nm* after sintering.

The cathode matrix sintered at 2000^oC by using 1-2 μm material is shown in Fig. 2. The porosity of this pellet is ~ 25%. The grain size in the micro composite cathode is around 2-3 μm. However, the scandia in the matrix is around 50-100 *nm*, still retaining nano size. The nano size scandium will have faster diffusion rate to migrate from the body matrix to the emission surface. It can be seen that the tungsten grain and pore size in the matrix are very uniform by using these powders made by the sol-gel method. The electron emission active materials, barium calcium aluminates ($BaO\text{-}CaO\text{-}Al_2O_3$) with a molar ratio of 4:1:1 are impregnated into the tungsten matix at 1650^oC for 1 min in a hydrogen atmosphere. Subsequently, the cathodes were cleaned in water to remove residual impregnates at the surface of the cathodes, and then annealed at 1000^oC under dry hydrogen for 20 *min* to remove remaining absorbed water and decompose any barium hydroxide and carbonate formed in the pores.

The high porosity of the tungsten matrix and the uniformity of the open pores directly control the uniformity and amount of the compound impregnated, and consequently affect the electron emission of an impregnated cathode. The uniform pore distribution makes the emission surface acquire more uniform barium, oxygen, and scandium distribution, thereby improving the emission uniformity and lowering the work function of the emission surface. This kind of cathode in which nano size Scandia is dispersed uniformly may be more resistive to ion bombardment [17].

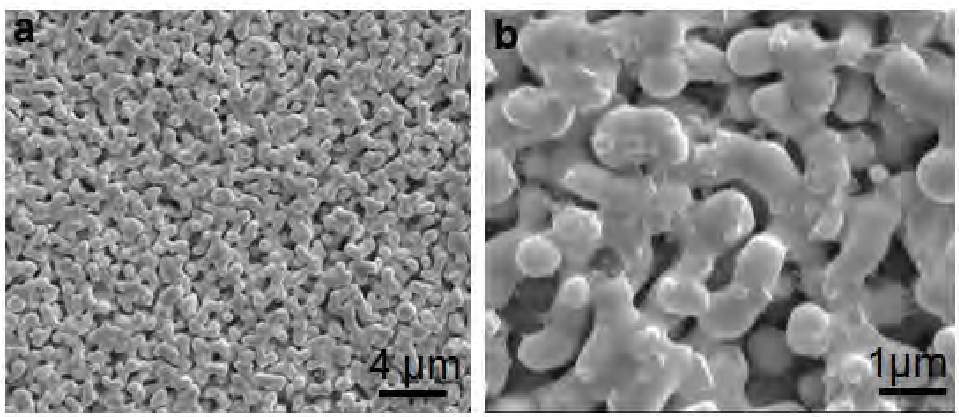

Fig. 1 (a) and (b) SEM images of scandate dispenser cathode pellet made from 500-700 *nm* powder with different magnifications.

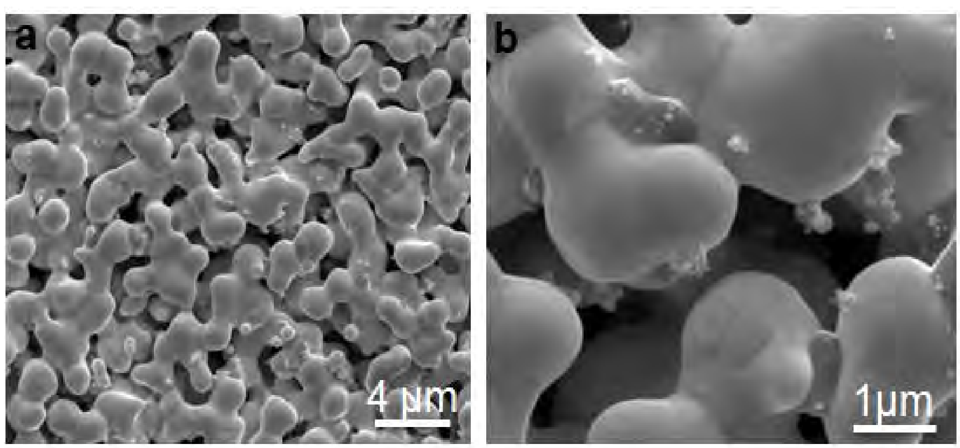

Fig. 2 (a) and (b) SEM images of scandate dispenser cathode pellet made from 1-2 μm powder with different magnifications.

2.2 Cathode nano machining

The last operation in the cathode fabrication process is machining the sintered pellet to the desired cathode shape. Since the porous tungsten with impregnated active materials is hard and fragile, this is a difficult procedure. In the DARPA HiFIVE program, the small size elliptical cathodes are required to be manufactured with a smooth surface, sharp edges, and high tolerances (0.813 ± 0.013 *mm* x 1.016 ± 0.013 *mm* emission surface). Nanocomposite scandate dispenser cathodes have excellent performance; however, the cathode pellets are very fragile since they are sintered at low temperature to have nanosize structure in the matrix. During the machining process, the surface of the porous material often appears to be smeared by the cutting tool, which closes the pores. The collapsed cathode pores will cause poor or low electron emission. This smearing effect is due to cathode material being distorted and pushed into adjacent cavities by the tooling, rather than being cut away cleanly. A similar issue can manifest itself in a different way near the edges of the cathode. Along the edges there is little material support for the machining operation, so there is a strong likelihood for cathode material to break away, leaving behind a chipped, rough edge. Specail attention must be given to the maching operation to ensure the final dimensions are precisely adhered to without smearing metal over the pore opennings on the surface [22-24]. The solution for these machining difficulties is to reduce the cutting pressure, through the use of diamond tooling and a steady, precise machine. Conventional computerized numerical control (CNC) mills have difficulty meeting these critical fabrication tolerances. Thus, we developed a micron size Sc_2O_3-added tungsten powder technique and an appropriate microcomposite scandate dispenser cathode fabrication process to produce high current density cathodes. The larger size particles offer a structure that is more robust, which greatly alleviates fabrication difficulties regarding edge and surface quality [20].

However, we were fortunate to have access to the prototype NN1000, a CNC mill newly developed by Digital Technology Laboratory Inc. (DTL), a subsidiary of Mori Seiki [25-26]. This machine offers technology that can machine nanocomposition scandate dispenser cathodes to the required shape with high quality. The NN1000 is a 5-axis CNC mill with nanometer command resolution. It features air bearing guideways, laser scale position sensors, linear drive motors, and anti-vibration technology that provide a very precise and stable platform for machining.

Cathodes are machined in two stages: a roughing operation, followed by a finishing operation. For roughing, the material can be aggressively removed with conventional tungsten carbide tooling. Some smearing and chipping will occur, but so long as sufficient stock material remains it will not adversely affect the final product. We found that a stock allowance of 50 *microns* was sufficient. After roughing, the tools are switched for the finishing operation. First, the sidewalls, base, and transition contours are machined. To facilitate this operation, a 0.762 *mm*, carbide ball mill with an amorphous diamond coating was used. The cutting parameters used were a spindle speed of 55,000 *RPM*, feed rate of 100 *mm/min*, axial depth of cut of 5 *microns*, and the radial depth of cut was 20 *microns*. This tooling allowed a smooth contour for the elliptical to round transitions with minimal chipping. Some smearing occurs here; however, since these sections of the cathode are not the emission surface, it is of no consequence. The top emission surface received special treatment, since this surface must have open pores and excellent edge definition. A mono-crystal, single flute, 4 *mm* diamond face mill was used. The cutting speed was 55,000 *RPM*; however, the depth of the cut and feed rate varied depending on the specific material. The depth of cut started at 10 *microns* per pass to remove blemished material, but as the final dimension is approached, the depth of the cut is reduced to minimize cutting pressure, with the final pass at a depth equal to the grain size of the material. The feed rate was calculated so that the leading edge of the tool should contact any particular cathode grain only once per pass;

therefore, the tool advance per revolution is the same as the grain size. For example, with a grain size of 500 *nm*, we would use a feed rate of 27.5 *mm/min*.

Figures 3 and 4 shows the SEM images of the machined elliptical scandate dispenser cathodes with nano and micro composite, respectively. It can be seen that the use of the NN1000 in conjunction with diamond tooling produces a smooth surface finish without surface smearing of the pores. Traditionally, the dispenser cathode would be machined using an infiltrant, usually plastic or copper, which acts as a lubricant during machning and maintains an open-pore structure. After machning, the infiltrant has to be completely removed from the tungsten matrix wihout introduction of any contaminants. The infitration and subsequent removal process are time consuming and a possible source of contamination. Our cathode fabrication process does not require the use of any infiltrant materials; consequently, no contamination is introduced.

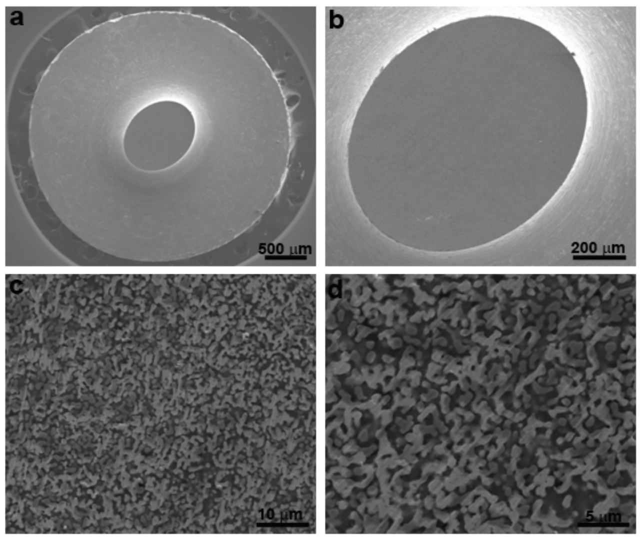

Fig. 3 SEM images of the machined elliptical scandate dispenser cathode made from 500-700 *nm* powder with different magnifications.

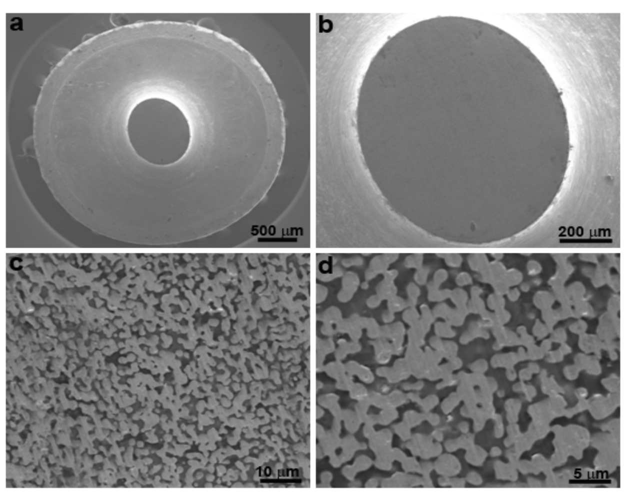

Fig. 4 SEM images of the machined elliptical scandate dispenser cathode made from 1-2 μm powder with different magnifications.

3. Cathode testing apparatus

A number of vehicles have been used for cathode testing. These include: cathode testing UHV cubes with a CSD configuration, modified UHV cubes with a real gun structure, and Pierce CLTV for cathode testing.

3.1 Cathode testing cubes with a CSD configuration

The cathode testing UHV cube systems with a CSD configuration are shown in Fig. 5. The simplicity of design, comprised of a rectangular copper anode and heater assembly, provides ease of fabrication. This assembly was designed and built to test the cathodes fabricated by using different recipes. In order to compare the performance of different cathodes, all cathodes including commercial ones were fabricated with the same size pellets (3.50 *mm* in diameter, 3.0 *mm* in thickness as the same as the heater cup inner dimension), and are tested under the same conditions. The distance between the copper anode and the cathode in each CSD was fixed at 1.0 *mm*. Great care was taken to eliminate as many problems associated with CSD tests as possible [27]. The cathodes was machined to fit very well with a titanium-zirconium-molybdenum **(**TZM**)** heater cup that was surrounded by heater shield to prevent the heat radiation under high vacuum. The cathode temperatures, in degrees centigrade brightness ($^{o}C_{br}$), were measured on the pellet surface using a disappearing-filament optical pyrometer through the glass window. The CSD was only designed for pulsed measurement. It is very convenient to install and remove the cathode from each CSD. One can therefore quickly and efficiently obtain comparative cathode testing results to select the correct fabrication procedures of cathode for high current density emission.

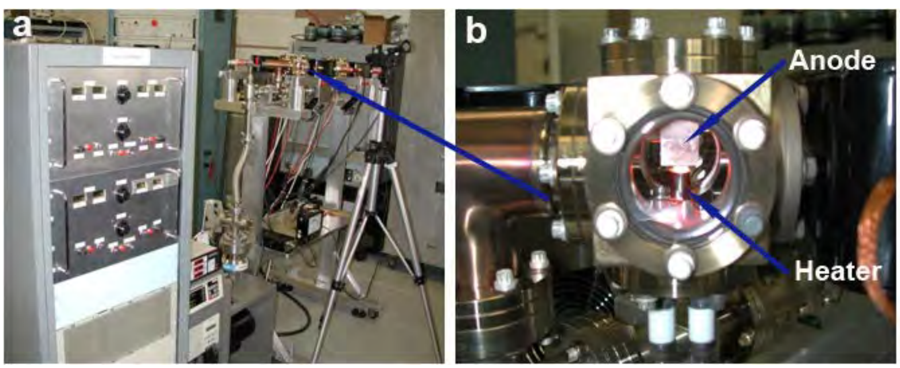

Fig. 5 (a) Cathode testing UHV cube systems with four cubes; (b) One cathode testing cube employing a CSD configuration.

3.2 Modified cube in an actual gun configuration

Most of the reported emission properties have been obtained with CSD structures. However, it has been found that the anode effect in diode structures impacts the cathode emission to some extent, especially during life tests. In contrast, testing cathode performance in electron gun open structures will minimize the influence from the anode. Furthermore, the testing results are useful reference for application of cathodes in VEDs. This work is intended to design an electron gun type assembly comprised of cathode, focus electrode, and anode/collector to test the high emission current density cathodes synthesized in our group in an actual electron gun type configuration. The simple geometry of this gun structure and anode design provides for ease in fabrication and accommodates the electron beam gradually in the collector for better power dissipation and cooling channels design. An actual electron gun configuration was designed for cathode pulsed test of 3.50 *mm* diameter scandate cathodes for a maximum current density of J ~ 50 A/cm^2. The modified cube system was designed and developed as shown in Fig. 6, which is very similar to an actual gun configuration, but allowing for ease in cathode installation and removal. The anode with an adjustable spacing is moved away from the cathode during activation to minimize contamination by evaporation from the cathode. The system is under testing.

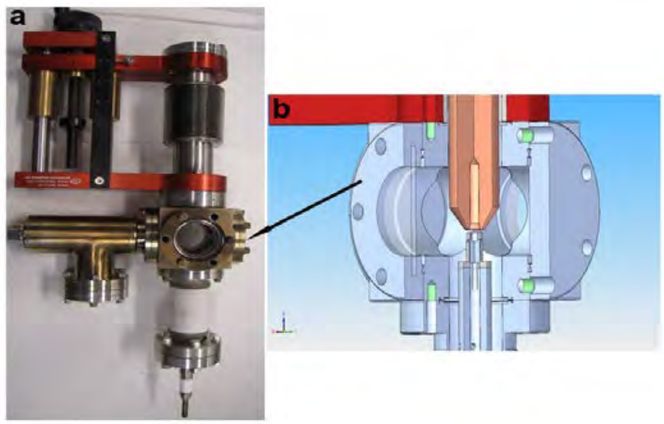

Fig. 6 (a) Modified UHV cube with real gun configuration; (b) schematic drawing of the inner structure of the Modified cube including the collector, focus electrode, cathode and heater etc.

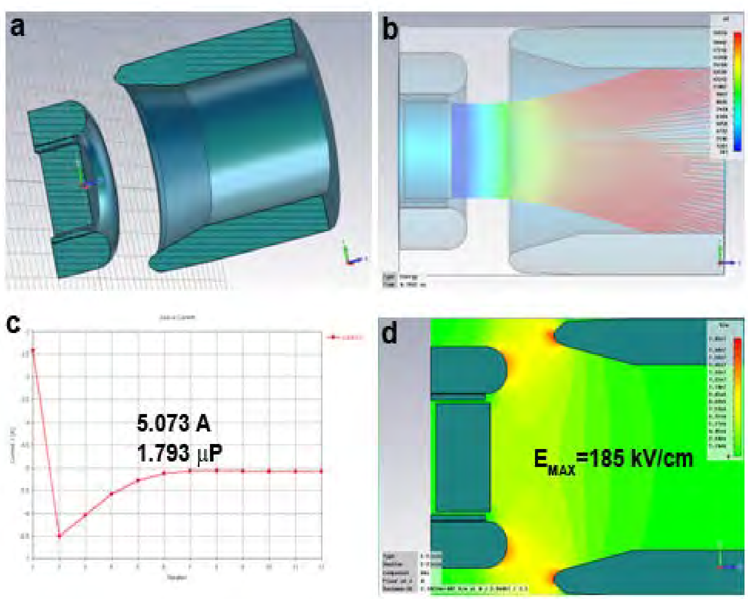

Fig. 7 (a) Electron gun model that includes cathode, focus electrode, and anode/collector; (b) Electron beam trajectory being dissipated in the anode/collector; (c) Extracted current 5.073 *A*; (d) Electric field lines contour plot showing a maximum field of ~ 185 *kV/cm*.

As the design was required to test cathodes operating up to ~ 50 A/cm^2, further optimization of the gun assembly was conducted for a gun voltage of 20 *kV*. The CST particle studio software simulation model is shown in Fig. 7 (a) and the beam transmission is shown in Fig. 7 (b). For 20 *kV* gun voltage, a current emission of 5.073 *A* (J ~ 52.73 A/cm^2) is produced as shown in Fig. 7 (c) with a gun perveance of 1.793 μP. The electric field contour plot is shown in Fig. 7 (d); this shows a maximum field of 185 *kV/cm*, which is a reasonable number to prevent arcing and electric breakdown in pulsed mode cathode testing.

3.3 CLTV with a Pierce gun construction

The CLTV with a Pierce gun construction was employed to test the cathode emission properties and their life time at high current density and CW operation. The schematic drawing and picture of the CLTV for both pulsed and CW testing are presented in Fig. 8 (a) and (b). The CLTV employs metal-ceramic construction and is provided with a conventional linear-beam-tube anode, a beam tunnel, and a collector. To measure temperature easily and accurately, a sapphire viewport is configured in the electron gun testing vehicle. The temperature was monitored by an optical pyrometer. It is designed to replicate the cathode operating conditions in VEDs.

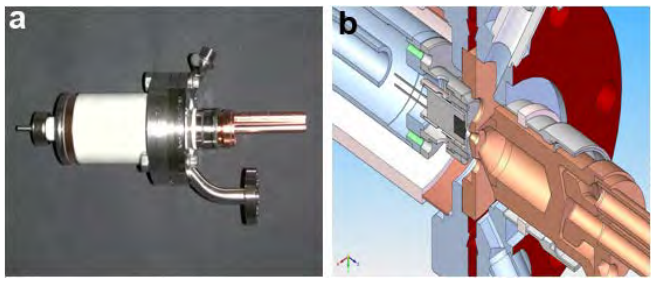

Fig. 8 (a) (b) schematic picture and drawing of cathode life testing vehicle for both pulsed and CW testing.

4. Cathode testing results

The emission performances of Sc_2O_3-added tungsten dispenser cathodes have been tested in both CSDs with pulse mode and CLTVs with a Pierce gun construction with CW mode.

4.1 Pulsed tests

In the CSD testing system shown in Fig. 5, the cathode with 3.5 *mm* ID and 3.0 *mm* thickness was assembled with a TZM heater. The anode-cathode distance was fixed at 1.0 *mm*. The cathode temperature was measured by an optical pyrometer. The cathode was activated up to 1150^oC_{br} for several hours. The system pressure was maintained at $<10^{-9}$ Torr during cathode testing. A high-voltage, 2 μs duration pulse with a repetition rate of 20 *Hz* from a modulator was applied to the cathode/heater assembly. Electron emission current was measured by an oscilloscope observing the voltage through a current transformer.

Typical I-V plots at different temperatures are used to evaluate the emission capability. The space-charge-limited (SCL) current densities were determined by Child-Langmuir (three halves powder) law, from the 1.5 slope of the LogI-LogV plot. Figure 9 shows that the emission characteristics of a cathode made by 500-700 *nm* Sc_2O_3-tungsten powder at different cathode temperatures. The SLC current density at 915^oC_{br} is up to 38 A/cm^2, and up to 80 A/cm^2 at 1050^oC_{br}. Actually, the upper current limit is due to the occurrence of arcing when the high voltage is applied and not cathode emission capability. The grain size of the tungsten in the cathode is 800-900 *nm* after being sintered at 1700^oC. This cathode pellet is mechanically strong enough for machining. The concentration of Sc_2O_3 in the initial Sc_2O_3-added tungsten powder is 3.65 *wt%*. From our experience, the Sc_2O_3 concentration with 5.0 *wt.%* is optimum. For example, space-charge-limited current densities of 40 A/cm^2 at 850^oC_{br} and 170 A/cm^2 at 1050^oC_{br} have been obtained using a 300-*nm* Sc_2O_3-added tungsten powder with 4.77 *wt*.% Sc_2O_3 [10]. We will test some cathodes with 5.0 *wt*.% Sc_2O_3 concentration and made by using the larger particles around 500-700 *nm*. These cathodes will be sintered at high temperature to form the porous matrix that is mechanically strong enough to be final machined. These cathodes are expected to have high current density and long-life time at low operation temperature. However, the Scandia concentration has a significant effect on the morphology of the tungsten powder. The synthesis conditions become more critical to obtain spherical shape of tungsten with high concentration of Scandia.

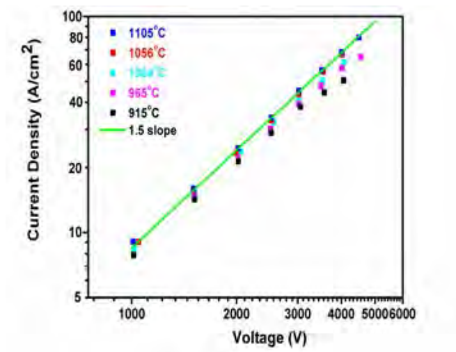

Fig. 9 Emission characteristics of nanocomposite cathode made by using 500-700 *nm* powder at different cathode temperatures.

4.2 CW Tests

In order to reduce the heat power to the collector because of the high current emission, the CLTV is designed to have: 0.4 *mm* diameter emission, ~ 4 *kV* DC, 1.0 *mm* distance between anode and cathode, 0.2091 μP, and 42 A/cm^2 current emission into a water cooled collector. The cathode matrix with 3.5*mm* diameter is covered by the focus electrode with a 0.4 *mm* diameter

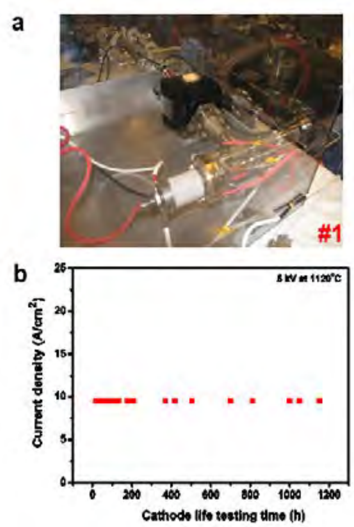

Fig. 10 (a) Cathode life testing vehicle #1 under CW testing; (b) The life testing results of CLTV #1 at 1120^oC and 5 *kV*.

Tab. 1 The comparison of the simulation data and experimental results based on the gap between cathode emission surface and focus electrode in the CLTV #1.

	Design values	**Simulation imitating experimental setup**	**Experimental Results**
Vb	4 *kV*	4 *kV*	4 *kV*
D	1.08 *mm*	1.08+0.1=1.18 *mm*	1.08+0.1=1.18 *mm*
Ib	52.89 *mA*	10.89 *mA*	11.20 *mA*
P	0.2091 μP	0.043 μP	0.043 μP
J	42 A/cm^2	8.67 A/cm^2	8.92 A/cm^2

hole in the center for the low capacity collector. Consequently the emission surface is 0.4 *mm* diameter and the space from the cathode to the anode is about 1.0*mm*. In CLTV #1 shown in Fig. 10 (a), the emission current density was above 10 A/cm^2 in CW mode for more than 2000 *hours* shown in Fig. 10 (b). There is a gap of 100 *microns* between the cathode emission surface and focus electrode in the CLTV #1. From CST simulation, we found that the perveance was consequently smaller than design goal, and the emission current density is much lower than our expected value. The experimental testing results are matched very well with the simulation data shown in Tab. 1. The second CLTV gun with reduced FE gap (30 *micron*) was tested. The electron emission is very sensitive to vacuum pressure. When the vacuum reached to 10^{-9} Torr, the current emission finally rose to 47 A/cm^2 CW. Unfortunately, the test time at the high current density was only ~50 *hrs* due to a vacuum leak. From our CST simulation, it is suggested that with a cathode move of 100 *microns* toward anode, this new design will allow for up to 100 A/cm^2 CW. The CLTV #3 gun with a cathode out of 70 *microns* (measured after assembly) beyond focus electron is under testing. Preliminary results in CLTV #3 show collector current density 104 A/cm^2 at 1040^oC_{br} at 4 *kV*, and up to 56 A/cm^2 at 960^oC_{br}. We plan to start conditioning for 40 A/cm^2 CW which is the design value for the 220 *GHz* sheet beam traveling-wave tube (SBTWT) amplifier.

5. Conclusions

Sol-gel processing combined with careful sintering leads to nano- and micro-structured and composite Sc_2O_3-added tungsten cathodes with uniform grain and pore size, appropriate spatial and chemical distribution of Scandia and other active species and improved uniformity of electron emission. These cathode pellets can be successfully machined with high precision by nano CNC machining without altering or plugging the pores. The emission performance of nanocomposite scandia-added tungsten dispenser cathodes, have been tested both in the UHV cubes with a CSD configuration under pulse mode and in CLTV with a Pierce gun configuration under CW mode. A space charge limited current density of 38 A/cm^2 at 915^oC_{br}, and 80 A/cm^2 at

1050^oC_{br} have been obtained by using 700 *nm* Sc_2O_3-added (3.56 *wt*.%) tungsten powders. The cathode was sintered by using 700 *nm* initial Sc_2O_3-W powders at 1700^oC, so the cathode pellets are mechanically strong enough for machining. In the CLTV with a Pierce gun configuration under CW mode, 45 A/cm^2 dc current density was obtained. The CLTV #3 gun with a cathode out of 70 *microns* beyond electron focus obtained collector pulse current density with 104 A/cm^2 at 1040^oC_{br} at 4 *kV*, and up to 56 A/cm^2 at 960^oC_{br}. This CLTV will be under CW life testing with 40 A/cm^2 current density.

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