Opportunities in Cathode Research Enabled by Advanced Nanoscale Material Control and Understanding

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Abstract: *New cathode technology is needed to enable the development of next-generation vacuum electronic devices. By exploiting recent advances in materials growth, processing, and characterization capabilities, opportunities exist in cathode research to better control and tailor the nano/micro-scale structure and composition of emitter materials and to develop an understanding of the critical material properties needed for enhanced emission capabilities.*

Keywords: Thermionic cathode; scandate cathode; dispenser cathode; nanostructured emitter; work function.

Introduction

Although the field of vacuum electron source technology is over 100 years old, it is still vitally important in our modern lives and remains the subject of active research. In fact, the numerous electron sources developed over the past century have been a critical enabling technology for a broad range of applications ranging from space satellites to large-scale accelerators. The thermionic cathode is especially versatile, coming in various sizes and configurations that can be customized for electron-based devices ranging from high-resolution scientific instrumentation to high-power amplifiers for radar and communications. While significant advances were made in thermionic cathode technology throughout much of the 20th century, new cathode development has remained somewhat stagnant in recent years due, in part, to the limited capabilities of established fabrication and characterization techniques. However, recent advances in materials growth and processing technology provide an important opportunity for cathode researchers to better control and tailor the nano/micro-scale structure and composition of emitter materials. Equally important, advanced characterization and analysis techniques are now able to probe the material properties on a nanoscale level, thereby providing critical insight into the emission dynamics. This paper will first review the challenges in cathode development and the current status of thermionic cathodes, and it will then highlight several opportunities for advanced cathode development enabled by nanoscale control / understanding of material properties.

Challenges in Cathode Development

Cathode research is very challenging due to the complexity of the electron emission process, with the specific issues depending on the type of emission mechanism employed. Regardless of the emission mechanism, however, the emission process is strongly dependent on the size of the energy barrier (i.e., work function) that electrons must overcome at the surface. The work function is, in turn, critically sensitive to the atomic-scale properties of the surface, and even small changes in the surface composition or structure can dramatically affect the barrier. The emission process is also dependent on the bulk electrical properties that govern and sustain the electron supply to the surface. As such, the key criteria for cathode materials are (1) lowest-possible *work function*, (2) sufficiently high *electrical conductivity*, and (3) *stability / robustness* during operation. It should be noted that robust operation is no small feat since the emission mechanisms used to liberate electrons place extreme demands on the material. It is critical, therefore, to understand how the surface and bulk properties behave under practical operating conditions (e.g., thermionic emission) in order to control and optimize the cathode performance.

Status of Existing Thermionic Cathodes

Metal Cathodes: Refractory metal cathodes such as tungsten (W) are *very robust*, with high melting temperature and mechanical strength. However, W has a *high work function* (~ 4.6 eV) and requires high operating temperatures (~2000°C) that can be unacceptable for many applications. As such, W cathodes are usually limited to current density (J) below 1 A/cm^2 to avoid rapid evaporation and short lifetime. Conversely, the binary compound LaB$_6$ has a *low work function* (2.7 eV) (among stable metals) as well as a high melting point, making it an ideal thermionic cathode. However, the low-work-function surface is relatively *reactive,* and therefore LaB$_6$ cathodes are limited to applications with good vacuum conditions.

Oxide Cathodes: Oxide cathodes, such as BaO, are insulators that become activated through the generation of oxygen vacancies during cathode heating. In this process, oxide cathodes become n-type semiconductors with *very low work function* (i.e., 1.5 eV for BaO) that allows for very-low-temperature operation. Although extremely reliable and stable, oxide cathodes have relatively *poor electrical conductivity* which limits the DC emission to $J \leq 1$ A/cm^2 at $T < 700$°C.

Dispenser Cathodes: Dispenser cathodes were developed to provide higher current density for more demanding applications. The dispenser structure consists of a porous W substrate that is impregnated with a Ba compound. Upon heating, Ba diffuses to the W surface and forms a Ba-O dipole layer that *lowers the work function* to 2.1 eV (or ~1.9 eV with further surface optimization). Although Ba desorbs at elevated temperature, it is continually replenished by Ba diffusion from the bulk. As a result, dispenser cathodes provide J ~ 5 - 10 A/cm^2 at T~1000°C.

As vacuum electronic devices have moved into higher power / frequency regimes, the demand for higher current density has increased as well. Unfortunately, dispenser cathode lifetime becomes unacceptably short at J > 10 A/cm^2 due to Ba depletion. To overcome this limitation, it is necessary to substantially decrease the work function, but a lower-work-function dispenser cathode has not been developed in spite of extensive efforts over the past 40 years. However, it should be noted that excellent emission characteristics have been reported from dispenser cathodes after adding scandium oxide (Sc_2O_3) into the W powder or Ba compound or onto the surface (e.g., J ~ 100 A/cm^2, work function < 1.5 eV) [1]. Nonetheless, a commercial scandate cathode has yet to be developed due to problems with reproducibility, uniformity, and robustness. Moreover, without reproducible cathodes available for scientific study, an accurate scandate emission model has not been developed and the role of scandium is still not understood.

Opportunity for Advanced Cathode Development

Scandate Cathodes: In the early 2000s, Chinese researchers employed a new processing approach wherein sub-micron- and micron-sized W powders were coated with Sc_2O_3 nanoparticles in liquid solution prior to sintering. This doping approach created a more intimate contact between the W and Sc_2O_3 particles and a more homogenous distribution of nanoscale Sc_2O_3 material throughout the bulk. Importantly, reproducible cathodes have been produced that can be optimized through independent control of the relative W / Sc_2O_3 particle size and concentration, resulting in exceptional emission characteristics (e.g., J ~ 100 A/cm^2 at T ~ 1000°C) [2]. Similar scandate fabrication efforts have been ongoing in the US, and a collaborative research program was recently established (through DARPA funding) to develop a scientific understanding of the scandate emission mechanism [3]. Characterization studies are in progress that employ high-resolution microscopy / spectroscopy and theoretical modeling to evaluate the nanoscale surface properties of successful scandate cathodes, and important insight has already been gained about the underlying emission dynamics.

Conductive Oxide Cathodes: The DC emission capabilities of oxide cathodes could be increased substantially by improving the electrical conductivity of the oxide material. By exploiting recent advances in controlled thin film growth techniques, an opportunity exists to fabricate crystalline oxide materials with tailored band structure and doping characteristics that may provide higher electrical conductivity and improved electron transport properties. Additionally, new classes of novel oxide compounds are being designed and engineered based on the predictions of advanced computational studies that screen for work function, conductivity, and stability [3].

Nanostructured Emitter Devices: By exploiting advanced nanofabrication techniques, opportunities exist to design custom emitter structures that employ specialized or combined emission mechanisms, such as field- or photo-enhanced thermionic emission. More specifically, thermionic cathodes (or field emitters) can be used with a secondary-electron current amplifier designed to multiply the thermionic beam current while reducing the emittance. Such a current amplifier concept has been demonstrated using tailored single-crystal diamond films [4], and further development of diamond electron amplifiers is being supported by an Army Research Office program. More generally, other epitaxially-grown ultrawide bandgap semiconductor materials and heterostructures are currently being explored, with future opportunities to exploit potential electron injection mechanisms and low surface barriers for the development of novel cold cathodes.

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References

1. Gartner, G., P. Geittner, H. Lydtin, and A. Ritz, "Emission Properties of Top-layer Scandate Cathodes prepared by LAD," Applied Surface Science, vol. 111, pp. 11-17, 1997.
2. Liang, W, Y. Wang, J. Wang, W. Liu, and F. Yang, "DC Emission Characteristic of Nanosized-Scandia-Doped Impregnated Dispenser Cathodes," IEEE Transactions on Electron Devices, vol. 61, no. 6, pp. 1749-1753, 2014.
3. Kirkwood, D. M. et al., "Frontiers in Thermionic Cathode Research," IEEE Transactions on Electron Devices, vol. 65, no. 6, pp. 2061-2071, 2018.
4. Yater, J. E. et al, "Secondary electron amplification using single-crystal CVD diamond film," Diamond and Related Materials, vol. 20, pp. 798-802, 2011.