Abstract: We report on CFE and TFE cathodes using (310) oriented hafnium carbide. These have been operated in UHV and temperatures from 300 K to 1900 K. Emission data show dramatic increases while operating at elevated temperatures due to work function lowering. Artificial faceting using FIB techniques shows promise for this cathode operating in Schottky emission mode.

Keywords: carbide; cold field emission; thermal field emission; Schottky emission; hafnium carbide; electron source.

Introduction
The theory of field emission from metals shows extremely high potential current densities from cold field emitters. Many have worked developing field emitters as reliable high intensity and brightness electron sources for a variety of applications. Thermionic emission and (cold) field emission are the two end points in a continuum of electron emission processes; in between lays the thermal-field emission (TFE) regime and Schottky emission (SE). It has long been known that W field emitters were capable of very high currents but generally required ultra-high vacuum for adequate stability and life of individual tips. The authors have searched for emitter materials which would retain the high current capability of W but would be more tolerant of a moderate vacuum (i.e. less sensitive to contamination and ion bombardment). We have obtained promising results with the transition metal carbides, particularly ZrC and HfC. Specifically, we achieved 25 mA dc at 2 x 10⁻⁸ torr from a large cone angle ZrC emitter and 100 mA pulsed (one microsecond pulses, power supply limit) at 3 x 10⁻⁹ torr. We expect that much larger currents could be achieved particularly for very short pulse operation.

These carbides have physical properties making them attractive for stable emission sources for several applications. The use of HfC(310) provides a relatively low work function (~3.4 eV) emitting surface that has a low evaporation rate, is resistant to ion bombardment and sputtering, has a high melting point (~4000 K), and a very low surface mobility. The robustness of this material allows for repeated cleaning via high temperature flashing without changing the geometry of the emitting end form. A typical clean CFE pattern is shown in Fig. 1 with the associated crystallographic planes delineated.

Experimental
Oriented and stoichiometric material is grown in our laboratory then ground, electrochemically etched and mounted in Vogel mounts. This mounting method allows flash cleaning to >2400 K and continuous operation at elevated temperatures. Experimental performance and modeling are reported for these HfC(310) field emission cathodes. Emission is studied over a range of temperatures from 300 K to CFE mode to ~1900 K which covers SE and TFE modes. Typical ZrO/W SE sources are processed to facet the (100) plane at the apex. Due to the physical properties of HfC we were required to artificially facet or truncate etched CFE emitters in order to operate them as Schottky sources in standard electron optical configurations.
Fig. 2 shows SEM micrographs of an etched field emitter having an approximate 100 nm tip radius. The very apex is removed and a flat truncation is created through the use of a Ga⁺ focused ion beam system. Operation of this cathode in SE mode will be reported at the conference.

![Figure 2: (a) Etched HfC(310) tip with ~100 nm tip radius. (b) Micrograph of same tip after FIB removal of apex creating an ~220 nm flat.](image)

Reduced brightness, energy spread, and moderate stability values were obtained in CFE operation with energy spread lower by a factor of two and brightness higher by a factor of ten than a ZrO/W Schottky source. Stable high current operation was also obtained through operation in TFE of an un-truncated HfC(310) emitters.

**Results and Discussion**

Emission noise and fluctuations arise from thermodynamic instabilities due to atomic motion of surface atoms. If activated by heating, surface atoms will move due to chemical potential gradients. In the absence of an electric field, surface atoms tend to migrate toward the shank and under high fields migrate toward the apex. It has long been known that surface tension and field forces contribute to blunting or build-up on W field emitters. However, HfC emitters have activation energy for surface migration (not precisely measured) which is very much larger than for W. This high activation energy for the carbide and more loosely bound surface contaminants mean that operation at elevated temperatures would keep the surface clean but not trigger geometric changes.

Operation at elevated temperatures (~1500 K) seems also to bring about surface chemistry changes as well. Past research⁵ is being re-investigated to see if these changes can be understood and controlled. Fig. 3(a) again shows a rather typical emission pattern with the (310) planes bright. After running at elevated temperatures from 10’s to 100’s of hours the emission current increases by as much a 1000x (5 μA to 5 mA) and is then stable. We have shown that this is probably due to work function reduction⁶ perhaps from an oxy-carbide formation. Fig. 3(b) shows the same emitter after reaching this high current state. These and other results show the unique and robust nature of the HfC emitter which can lend itself to improvements for several applications.

**References**


![Figure 3: (a) A typical field emission pattern from HfC where the (310) planes are bright; emission level is ~10 μA. (b) The emission pattern after running for ~300 hours at 1500 K. Here the emission has increased to ~1 mA.](image)