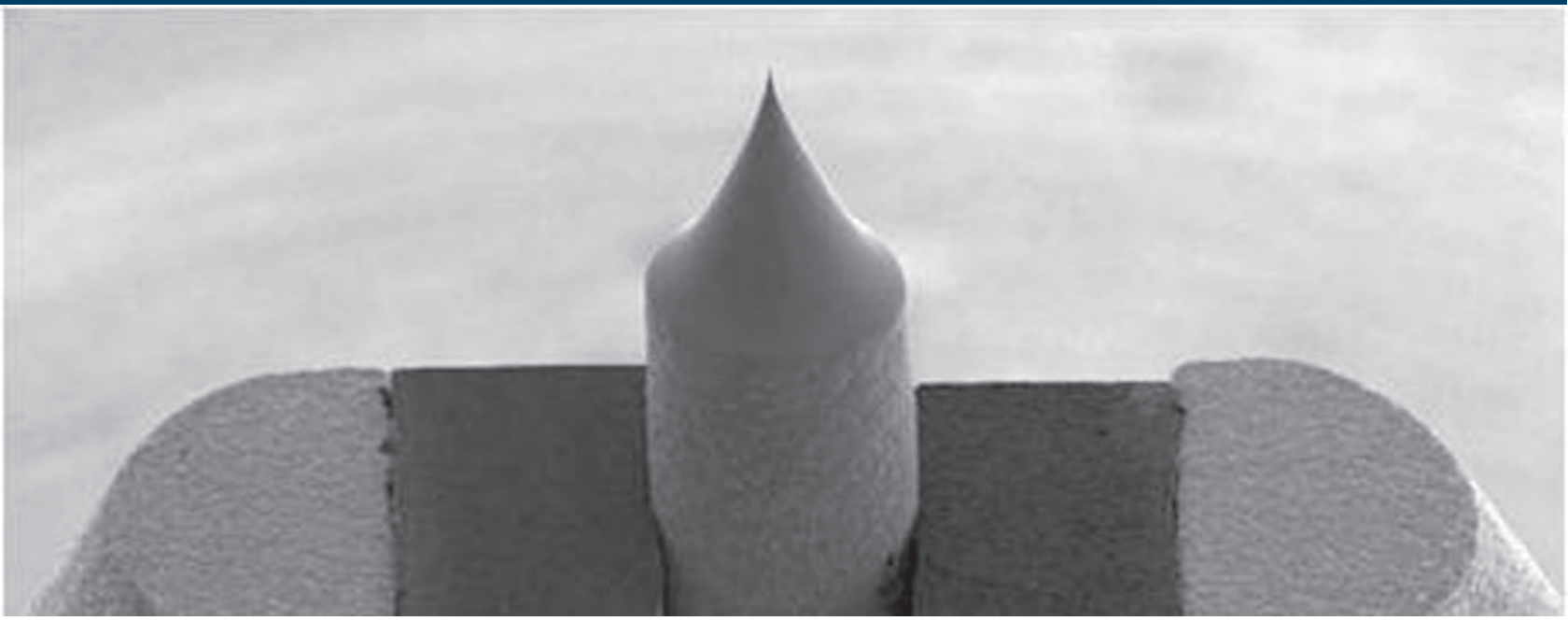
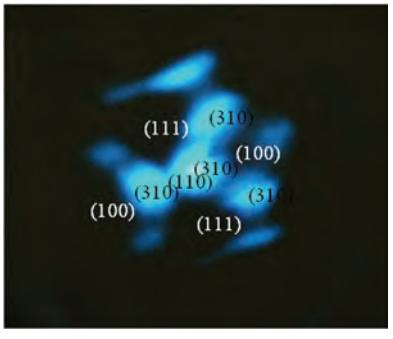
Transition Metal Carbides ~ Cold Field Emission Source

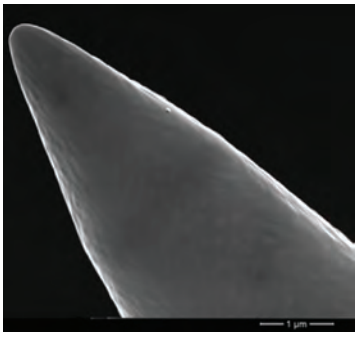


Field Electron Sources:

Carbide cathodes have electron emission properties making them attractive candidates for stable emitter sources in even moderate vacuum applications. HfC (310) has a relatively low work function axial emitting surface, Φ = 3.3 eV, a low evaporation rate, is resistant to ion bombardment and sputtering, has a very high melting point (~4200 K), and a very low surface mobility. These material properties allow the HfC emitter to be flash cleaned to ~2100 K in UHV without any degradation to the emitter end form. These properties enable the carbide field emitter to operate at high current densities and in a variety of conditions. Contact Applied Physics Technologies to discuss your particular needs and application.



Typical FEM image of a carbide cathode; (310) on axis, indicating major planes.



HfC (310) cold field emitter, electrochemically etched.

High Current Operation:

1) DC field emission from a single emitter: 25 mA
2) Pulse field emission from a single emitter: 100 mA
3) Field emission: 10^{-6} Torr air at 200 µA

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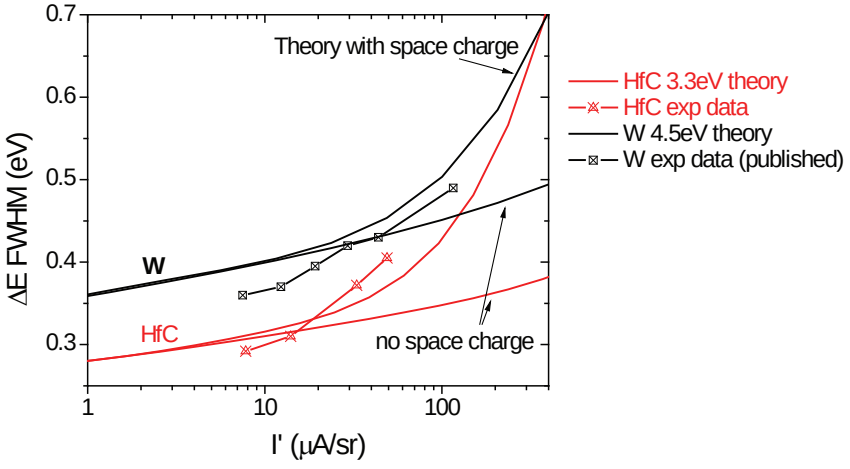
Field Emission from HfC (310)

Single crystal HfC has been evaluated as a cold field emission (T = 300 K) electron source for applications such as high resolution SEM/TEM and it has proven to be an excellent candidate for this use. Single crystal HfC was produced and fabricated into a cold field emitter. Angular intensity and reduced brightness were determined from experimental I(V) data. Experimental energy distribution data are shown below and are in agreement with modeling. The reduced brightness, energy distribution, and emission stability of HfC are compared to commercially available sources. HfC produced a higher brightness and a lower energy spread than a W cold field emitter or ZrO/W Schottky emitter (T = 1800 K). HfC shows a dramatic improvement in long term stability maintaining its emission level for one hour in moderate UHV conditions. This stability combined with a durability that allows for frequent flash cleaning without degradation of the emitter end form make HfC a highly promising cold field emission source.

An ideal electron source for a high resolution SEM/TEM application has a high reduced brightness (B_r), a minimal total energy distribution (TED), good long-term emission stability, and a long lifetime. Commonly used sources for these applications are Schottky emitters, ZrO/W operated in thermal field emission (TFE) mode (T = 1800 K, <1 x 10^{-9} Torr), and W run in cold field emission (CFE) mode. ZrO/W emitters are highly stable, but their relatively high TED can limit the resolution in a chromatic aberration limited optical system. W CFEs have a lower TED and a higher B_r than a ZrO/W source, but emission instabilities and changes in the emitter's end form, due to flash cleaning, limit its performance.

Total Energy Distribution

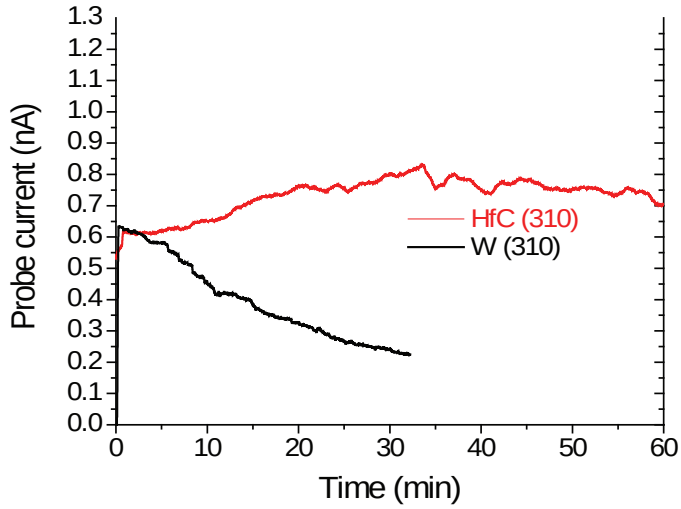
A simulation of the TED both with and without space charge was computed numerically to compare HfC and W. The geometric properties were identical: R = 175 nm, m = 0.5, and $\beta = 11429\ cm^{-1}$. The temparature was 300 K, work functions of 3.3 eV and 4.5 eV were used for HfC and W respectively, and the field was varied to obtain a range of I' values. The results of the simulation are compared to experimental data taken on a HfC emitter of comparable radius along with published data for W in the figure to the right.[1]



The reduced energy spread for HfC can be attributed to the 1.2 eV lower work function of the material. HfC can therefore provide a slight improvement in chromatic aberrations by the reduced energy spread or operate at a higher I' which can benefit image quality through improved signal to noise.

1. G.A. Schwind, G. Magera, and L. W. Swanson, J. Vac. Sci. Technol. B 24, 2897 (2006).

CFE Stability: HfC vs. W



- Emission stability after flash
- T=300 K
- 5 x 10^{-10} Torr
- R = 200 nm
- I' = 20μA/sr
- α = 4 mrad
- M ~ 100kX

Emission data was recorded for HfC and W using a defined probe with half angle of 4 mrad. Every effort was made to match the operating conditions for the two materials: the same system and test module were used, the radii matched, and the vacuum conditions were kept the same at 5 x 10^{-10} Torr. The probe current versus time is shown above where the HfC and W should benefit from better vacuum conditions, however in a real application this vacuum comes at a high monetary cost. A ZrO/W TFE source has dramatically better stability than CFE where one can expect very little emission drift over the >1 year life of the source yet some applications still choose a CFE source for the reduced TED.

Reduced Brightness vs. Energy Spread

The I' was used to calculate B_r which is plotted against the FWHM of the energy distribution shown below. Experimental TED data was also taken from a 550 nm radius ZrO/W emitter and is included in this plot. The ZrO/W energy spread of 600 meV corresponds to an I' of 0.3 mA/sr, typically the minimal mode of operation that will still maintain a stable end form, and should be used for comparison to the CFE sources.

The advantage in B_r shown by the two CFE sources is primarily due to the smaller virtual source size. The reduction in the energy spread over TFE is a benefit of the lower operating temperature. The offset between the HfC source and W is again attributable to lower work function of the HfC. The HfC source can deliver half the energy spread of a ZrO/W TFE source while simultaneously operating at ~5 X higher reduced brightness.

HfC(310) CFE

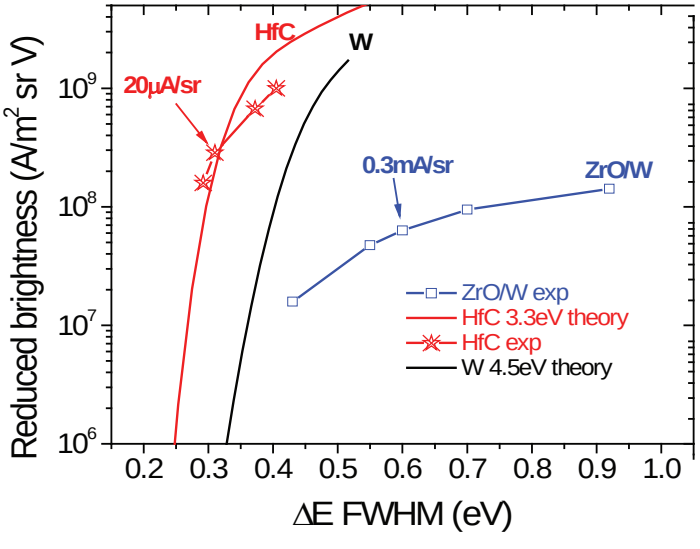
- ΔE = 325 meV
- B_r = 3 x 10^8 A/m^2srV
- I' = 20μA/sr

ZrO/W(100) TFE (Schottky)

- ΔE = 600 meV
- B_r = 6 x 10^7 A/m^2srV
- I' = 0.3 mA/sr (min. for stability @ 1800 K)

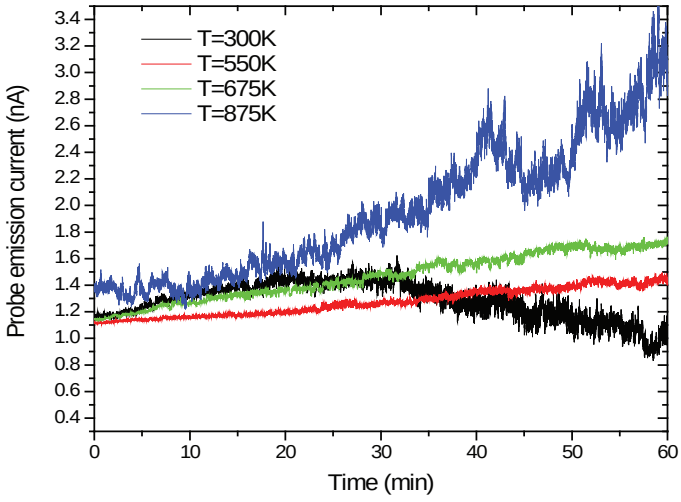
W(310) CFE

- ΔE = 375 meV
- B_r = 3 x 10^8 A/m^2srV

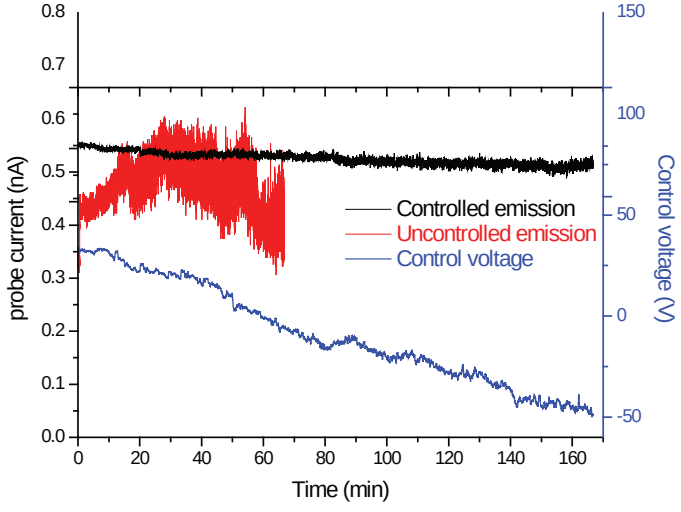


Beam Current Stability ~ as a Function of Emitter Temperature

The HfC source was operated at a range of temperatures to gauge the impact of heating on the emission stability of the source. This data was sampled at 5 Hz and is plotted to the right. Temperatures were estimated from a fit of optical pyrometer data. As the temperature is raised from 300 K the emission fluctuations are reduced; however, at 875 K, the fluctuations increase sharply. We believe that the improvement in stability is from a reduction in adsorbed contamination on the surface of the emitter. At the highest temperature, we believe that an increase in the mobility of contamination on the HfC surface and a change in the reactivity of the surface with this contamination negate any positive effects from reduced adsorption resulting in increased current fluctuations.



Controlled beam current traces



Probe current traces without feedback control (red trace) and with control (black trace). Shown in blue is the control voltage applied to the extractor. These data were recorded using feedback on the extractor through monitor current detection. Monitor current was recorded on the final beam limiting aperture.

HfC CFE outperformed W CFE in B_r, energy distribution, and emission stability. In general, CFE sources provide a higher B_r and lower energy spread than a TFE source. The model of energy distribution including a space charge component showed a good fit with experimental data. The emission stability from HfC CFE was significantly better than that of a W CFE when operated in modest UHV conditions. Slight heating of the HfC emitter improved the short term emission fluctuations while resulting in a relatively small increase in the FWHM of energy spread. Based on these results, HfC is shown to be an excellent candidate as a CFE source for SEM/TEM applications.

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