Recent Advances and Applications of Spindt Field Emitters

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Over the years, Spindt field emitter array cathodes have demonstrated unsurpassed emission performance, with current densities in excess of 2000 A/cm^2 from small 16 tip arrays,[1] currents in excess of 330 mA from 1-mm-diameter arrays,[1] emission modulation up to 10 GHz,[2] operation at temperatures of 4K to 800K,[1] and individual emitter tip peak currents of 3.5 mA.[2] Each different application places different demands on the emitter array. Here we discuss three developing applications, the associated emitter array cathode requirements, and the status of each application.

Application 1: mm-wave traveling wave tubes. TWTs require total currents >100 mA with average current densities exceeding 2-20 A/cm^2. With L-3 Technologies, SRI has demonstrated emitter array operation with useful gain in TWTs at C and X-Ku band.[3] As the operating frequency of the TWT is increased above 100 GHz, the diameter of the helical slow-wave structure must be decreased and the emitter array cathode emittance reduced to < 0.5 mm-mrad. We have modeled, designed, and fabricated arrays of self-focused emitters[3] that operate up to 10 μA/emitter to meet this need. We have demonstrated reduction in transverse RMS emittances by by a factor of 4, from ~ 1 mm-mrad to ~ 0.25 mm-mrad. Figure 1 illustrates SEM images of the developed self-focused, low-emittance array cathode.

Application 2: Magnet free ion pumps. Recent advances in quantum sensors and systems using cold atoms trapped in magneto-optical traps in compact vacuum vessels has created a need for small, magnet-free ion pumps. We have developed a 1-cc sized magnet-free ion pump that uses a Spindt cathode as the electron source. The cathode current requirement for this pump is only a few tens of microamps, which is easily achieved with a small array. A concern in this application is the lifetime of the cathode and probability and changes in the emitter tip work function due to the gas species being pumped. To mitigate such issues, we developed Spindt emitters with an iridium apex. Figure 2 shows one these completed pumps. These pumps have operated on sealed chambers for over 4 years.

Application 3: Mercury ion-based atomic clocks. The need for high-precision timing for space navigation has created a demand for compact atomic clocks. In collaboration with JPL,[4] a ~10-cc Hg ion based atomic clock has been developed. In this application the Spindt cathode is used to inject electrons into a quadrupole trap to ionize the Hg (10^{-8}T) in a He (~10^{-5}T) buffer gas. The absence of heat from the cathode is a critical component for producing a stable plasma and low-SWAP clock. Figure 3 shows a completed clock with an inset of a typical emitter used.

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[1] Zhu, Wei, ed. Vacuum microelectronics. John Wiley & Sons, 2001.

[2] Schwoebel, P. R., C. A. Spindt, C. E. Holland, and J. A. Panitz, Field emission current cleaning and annealing of microfabricated cold cathodes, J. Vac. Sci. Techol. **B19**, 980-987, 2001.

[3] Whaley, David R., et al. Cold cathode based microwave devices for current and future systems. 2018 31st International Vacuum Nanoelectronics Conference (IVNC). IEEE, 2018

[4] Hoang, Thai M., et al. Integrated physics package of micromercury trapped ion clock with 10−14-level frequency stability. Applied Physics Letters 119.4, 2021.

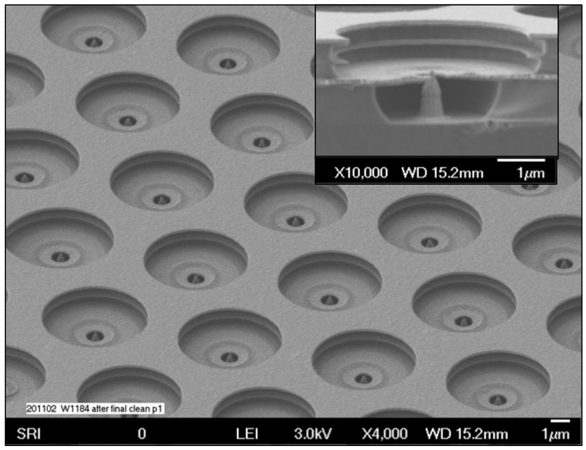

Figure 1: Portion of a 14,000 integral Focus Spindt cathode array.
Inset: Cross section of one of the integral focus emitters.

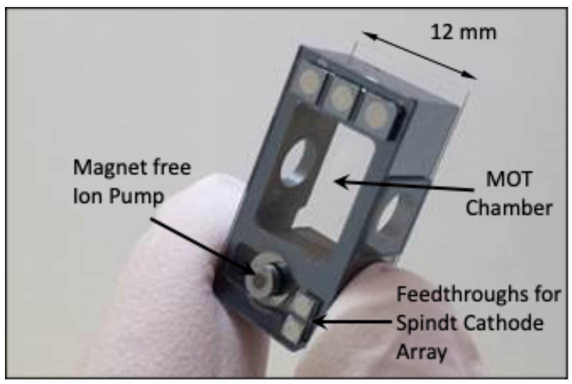

Figure 2: UHV miniature vacuum chamber used for magneto optical traps (MOT) employing a Spindt-cathode-driven magnet free ion pump.

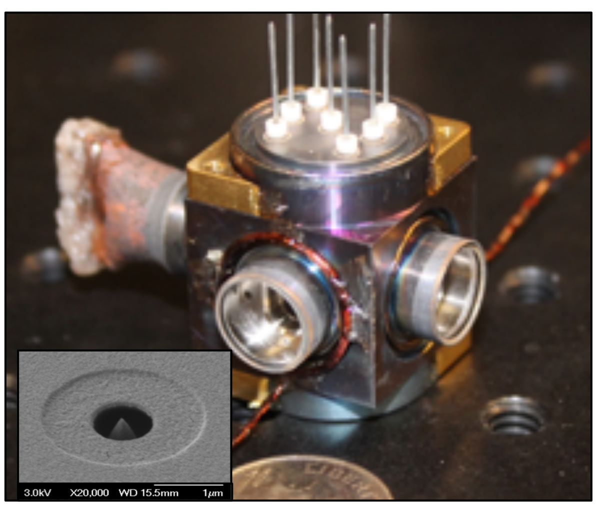

Figure 3: 10 cc pumpless micro-mercury trapped ion clock (M2TIC) prototype employing a 590-tip Spindt cathode array. Inset: Typical Spindt-type emitter in array.