Evaluation of the Characteristics of a Field Emission Cathode for Use in a Mercury Ion Trap Frequency Standard

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This article reports on the performance of a field emission array characterized for the purpose of replacing the filament in a trapped ion frequency standard. This dark electron emitter eliminates the need for the interference filter currently used in the trapped ion standard. While reducing the filament's unwanted light, this filter causes a significant reduction in the signal. The magnetic field associated with the filament is also eliminated, thus potentially improving the present stability of the trapped ion standard. The operation of the filament in the present system is described, as well as the associated concerns. The cathode considered for the filament's replacement is then described along with the experimental system. Experimental results, observations, and conclusions are presented.

I. Introduction and Background

Stability requirements desired of modern frequency standards, in the range of one part in 10^{17}, are nearly two orders of magnitude beyond the capabilities of hydrogen masers currently employed in the DSN. Because of the increased potential of achieving higher frequency stability, extensive research has focused on the development of trapped ion frequency standards [1].

The inherent stability of atomic frequency standards is completely defined by two parameters: the signal-to-noise ratio (SNR) and the line Q. The SNR determines the efficiency of the atomic resonance measurement procedure. The line Q represents the narrowness of the atomic resonant frequency.

Methods which increase the signal and suppress the noise are used to enhance the detection of the atomic resonance, increasing the SNR. The signal in the ion trap device is the fluorescence of the trapped ions, and the noise is due to stray light scattering from the optical pumping light and all other light sources. The principal source of noise is currently light emitted from the hot filament electron source. One way to improve the atomic resonance detection involves eliminating the interference filter required in the light detection system [1]. While suppressing unwanted light, this filter also significantly reduces the signal. Removal of the interference filter is feasible only if the filament is replaced with a dark electron emitter.

Atoms with narrow hyperfine structures are used to improve the line Q. Energy levels are broadened as the magnetic field gradient at the position of the ion cloud is increased. Elimination of magnetic field gradients internal to the ion trap will result in an increased line Q. The electron current emitted by resistive devices is dependent on the applied current, which induces a magnetic field gradient. Replacement of the filament with a non-resistive electron emitter reduces the associated magnetic field.

This article reports on the performance of a field emission array characterized for the purpose of replacing the filament in a trapped ion frequency standard. The operation of the filament in the present system is described, as are the associated concerns. The cathode considered for the filament's replacement is described along with the experimental system. Experimental results, observations, and conclusions are also presented.

II. Present System

In the development of a mercury ion frequency standard, hot filaments are used in the vacuum chamber to ionize confined mercury atoms, which are then trapped and illuminated with ultraviolet and microwave radiation. During initial operation of the frequency standard, electrons are emitted into the trap for half a second and are then turned off for two and one-half seconds. Two power supplies are necessary to pulse the electrons. One provides the power through the filament, and the other is used to float the filament to a negative potential of 300 V, accelerating the electrons to a positively charged collector. Because the filament is a resistive element, the most effective method of pulsing the electrons is to switch the high-voltage supply on and off, leaving the filament supply constant.

The operating parameters of the filament are 2 V at 1.4 A. This continuous 2.8-watt level of power keeps the filament white hot. The bright filament makes an interference filter necessary in the optical collection portion of the vacuum system. While all filament light is efficiently blocked from the photon detection system, this filter also blocks 60 to 70 percent of the signal. The result is that twice as much collection time is required to obtain the equivalent signal-to-noise ratio with the filter in place than without.

The filament's continuous current also generates an unwanted magnetic field in the trap. Internal magnetic field gradients produce line broadening in the mercury ion hyperfine transition, thereby reducing the line Q.

An evaluation of the characteristics of a cold cathode was initiated to determine if these problems could be eliminated. Because the cathode is not a resistive element, it does not produce unwanted light and eliminates the need for the interference filter. As the maximum current between the base and the gate of the cathode is 200 μA, four orders of magnitude less than the filament current, the resulting magnetic field would be greatly reduced. It is also possible to directly pulse the cathode, eliminating the magnetic field associated with the off time of the electrons.

III. Cathode Description

Field emission devices operate on the principle that applied electric fields at the surface of conductors cause electron emission. Efficiency of electron emission results from the choice of appropriate conducting materials and geometrically sharp conductor tips to achieve high electric fields. Limitations of these devices arise from the high potential necessary to generate these fields, typically 1000 to 10,000 volts. These high voltages generally cause current instability and limited device lifetime. Higher stability and longer lifetimes have been achieved by employing ultrahigh-vacuum environments, improving the sharpness of the pin used for emission, and decreasing the anode-emitting tip distance. Increasing the number of pins used for emission provides higher electron current, while reducing anode-emitting tip distance results in the achievement of the necessary high fields at much decreased applied voltages in the range of 50 to 200 volts.

The device used in this work was developed by Spindt et al. [2]. These field emission arrays are produced by a sandwich of conducting, insulating, and conducting materials. The manufacturing process consists of coating an oxidized silicon substrate with a molybdenum film, etching 10,000 holes through the various layers to the silicon, and forming molybdenum cones in the cavities. The bases of the cones are attached to the silicon substrate, and their tips lie in the plane of the molybdenum coating (Fig. 1). A negative potential applied between the molybdenum tips (base or cathode) and the molybdenum film (gate or anode) causes electron emission from the tips. A collector, positively biased with respect to the gate, attracts the electrons and allows for emission current measurements. The cathode is mounted on a TO-5 header with eight contact pins. Only two of these pins, the gate and the base, need exterior connections.

Manufacturer data indicate that emission current densities of 6600 mA/cm^2 are common with these cathodes, which have a packing density of 1.2E6 tips/cm^2. This density is strongly dependent on the geometry and biasing of the collector as well as on the proximity of the collector to the cathode. These arrays are capable of pulsed or continuous mode operation.

IV. Experimental Setup

For the initial turn-on of the cathode, it was necessary to achieve an ultrahigh-vacuum environment of about 1E–9 torr. For this purpose, a stainless steel vacuum chamber was assembled using mechanical, turbo, and ion pumps. An electrical feedthrough served as the connection to the base and gate of the cathode and also provided four attachments to the isolated portions of the collector. The collector used was an actual stainless steel ion trap consisting of an extraction grid, two end caps, and a cylindrical ring electrode. The extraction grid and the end cap closest to the cathode are constructed of stainless steel mesh, while other components are solid stainless steel (Fig. 2). The mount for the electron emitter was secured to the collector, approximately 1 cm away. Because contamination causes cathode shorts, it was necessary to clean the collector thoroughly. Therefore, a tungsten filament was inserted into the vacuum chamber prior to the positioning of the cathode.

When the pressure was below 1E–9 torr, the filament was operated and the collector was cleaned by electron bombardment. Before its use, the cathode is kept vacuum sealed to prevent destructive atmospheric contamination. Argon was introduced into the vacuum system to maintain the chamber's uncontaminated condition as the system was opened for the replacement of the filament with the cathode. The cathode is mounted in a standard transistor-type casing that is approximately the same size as the filament. Therefore, installing the cathode was merely a matter of removing the filament and inserting the cathode in its place, minimizing atmospheric contamination.

Two power supplies were used in series to extract the electron emission toward the collector held at ground potential. One provided power to the cathode, while the other established the cathode's negative biasing. A resistor was placed in series with the cathode in order to monitor the current provided by the power supplies. It is crucial to monitor the base–gate current of the cathode because destruction of the array can occur if this current is greater than 1 μA. At high base–gate currents, the tips melt to the gate and short the cathode. Current from the various sections of the collector was combined and monitored using an electrometer. The current supplied by the power supplies is equal to the combination of the gate–base current and the emission current collected by the collector.

The base pressure of the vacuum system was 5E–10 torr, lower than the manufacturer's suggested pressure of 1E–9 torr for the initial turn-on of the cathode. The emission current was monitored as the voltage across the cathode was varied between 50 and 80 volts. The current between the base and gate was determined by observing the total current supplied by the cathode's power supply and subtracting the collected emission current.

After the current–voltage relationship was determined, the cathode was isolated from the turbo and mechanical pumps by a valve. Helium was introduced into the vacuum system from an auxiliary port on the turbo pump to simulate the operating environment of the ion frequency standard. When the helium pressure had increased to 1E–5 torr, the valve between the turbo pump and the cathode was opened. Current was again monitored to determine the effect of the helium pressure on the emission characteristics of the array.

The cathode has operated continuously for a four-week period. During the first week of operation, two shorts occurred from the base to the gate. This damage was reversed by the discharging of a 1-μF capacitor that was charged to 30 V. The array was again able to emit with no variation in the current.

V. Results

The emission characteristics of the cathode were determined by varying the applied voltage. The voltage was varied between 55 and 80 volts, and 15 values of the emission current were measured. The data were obtained after the emission current had stabilized. The emission current, the total current, and the base–gate current are plotted against the applied voltage in Fig. 3. Figure 4 shows the plot of the same data for the helium environment. As can be seen in these figures, 75 volts will produce more than 50 μA of collectible emission current in either environment. The electron current needed in an ion frequency standard is dependent on the trapping time of the standard, which corresponds to a few microamps in the present system. The desired level of emission collected in the simulated trap is 30 μA. In both environments, the gate–base current was measured up to 20 μA, much higher than the 1 μA suggested by the manufacturer.

Comparison of the current versus voltage graphs of the two environments indicates that the helium pressure does not affect the emitting characteristics of the cathode, confirming predictions based on the short-term effects of a background gas (private communication, SRI). The lifetime of an array under a substantial amount of background gas pressure has not been determined; yet the cathode has operated for a period of three weeks at a helium pressure of 1E–5 torr without adverse effects on its performance.

Plots of log (I/V^2) versus 1000/V were generated to determine if the cathode followed the expected Fowler–Nordheim relationship of an emitting array [3]. The Fowler–Nordheim plots of the current and voltage should produce a straight line if there is consistent geometry of the tips and the emitting area and if the work function is constant. The uniform geometry of the cathode depends on the manufacturing process. The degree of deviation of the work function from a constant value increases as the contamination level of the environment increases.

Figures 5 and 6 are the Fowler–Nordheim plots using the total current and the applied voltage of the cathode. For both the ultrahigh-vacuum (UHV) and the helium background pressure environments, the experimental points are graphed along with the best fit lines. The best fits were obtained using a least squares fit method. The slopes of the best fit lines are –0.210 (±0.005) and –0.200 (±0.005) for the UHV and helium environments, respectively. The slopes have a 2.5 percent experimental error margin, reflecting the precision of the measurement equipment. Within this margin the slopes have the same value, indicating that there is no appreciable effect on the emission current due to the helium pressure.

As indicated by comparison of the Fowler–Nordheim plots of the two environments, the cathode is adequately designed and manufactured for application in an ion frequency standard.

VI. Conclusion

An electron source has a vital function in an ion frequency standard. The existing filament offers sufficient electron current for the function of this standard but brings with it inherent disadvantages, including undesired light and a magnetic field. A novel method for producing electron current in an ion trap which functions without the production of light or a magnetic field has been presented in this article. An electron emission array has been placed in a simulated ion frequency standard environment to determine if it is suitable as a filament replacement.

The study reported here indicates the cathode's compatibility with the existing system. This device provides confident replacement of the filament in an ion frequency standard and offers many advantages.

The similar sizes of the cathode and the filament provide for the interchangeability of the two with minor modifications in the existing system. The amount of the cathode-collected emission current is sufficient for use as an electron source. Since no indication of adverse effects of helium on the performance of the cathode was found, the compatibility of the cathode with the present system is enhanced.

The cathode's ability to generate electrons without producing light allows for the elimination of the existing interference filter, thereby increasing the collected signal by a factor of two or three, which improves the SNR. The negligible amount of current required for cathode operation, together with the ability of the cathode to operate in an efficient pulsed mode, eliminates the associated magnetic field generated when the filament is utilized. Because of the dependence of the line Q on the magnetic field, improvements in the line Q follow the reduction of the magnetic field.

This article reported on an electron-emitting device which will increase the inherent stability of the ion frequency standard. The replacement of the filament with the emission array improves both of the stability-defining parameters, the SNR and the line Q.

Acknowledgments

Much appreciation is extended to Capp Spindt and his SRI co-workers for their suggestions and for the constant availability of their expertise. Gratitude is also expressed to Dr. L. Maleki for his technical advice and suggestions in the preparation of this article.

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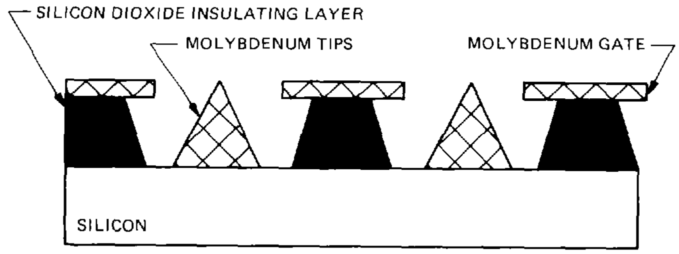

Fig. 1. Schematic diagram of a field emission array

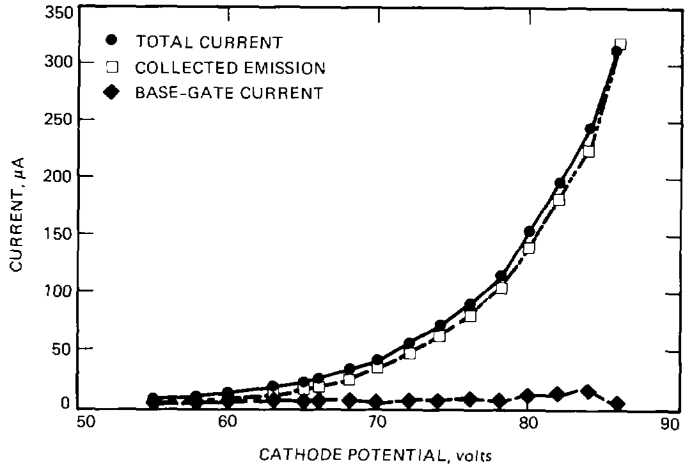

Fig. 3. Current versus voltage plot for the cathode with a background pressure of 1E−9 torr

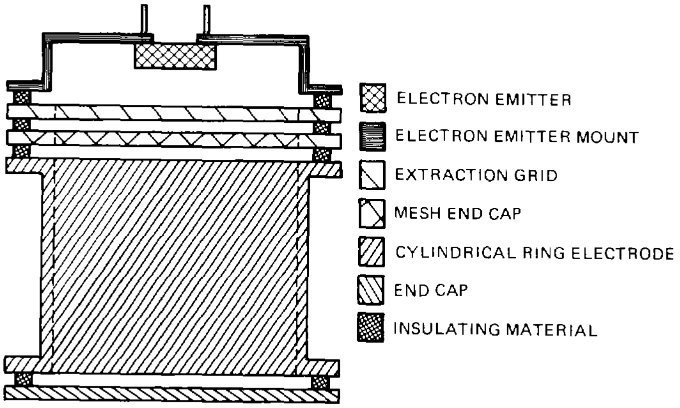

Fig. 2. Diagram of the electron emission collector; mount supports either a filament or a field emission array

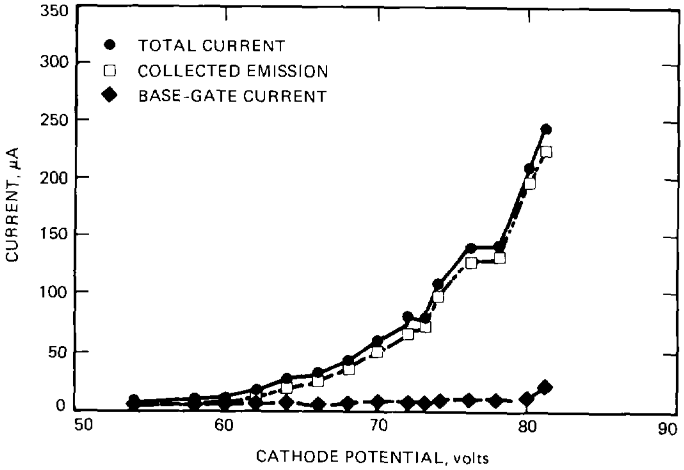

Fig. 4. Current versus voltage plot for the cathode with a helium background pressure of 1E−5 torr

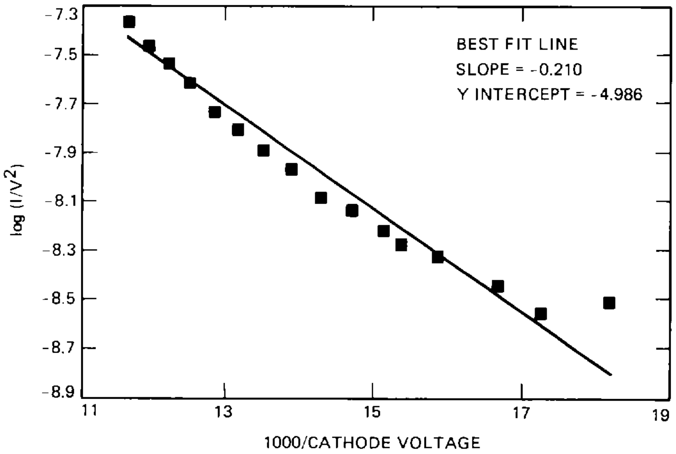

Fig. 5. Fowler–Nordheim plot of cathode total current and applied voltage (background pressure of 1E–9 torr)

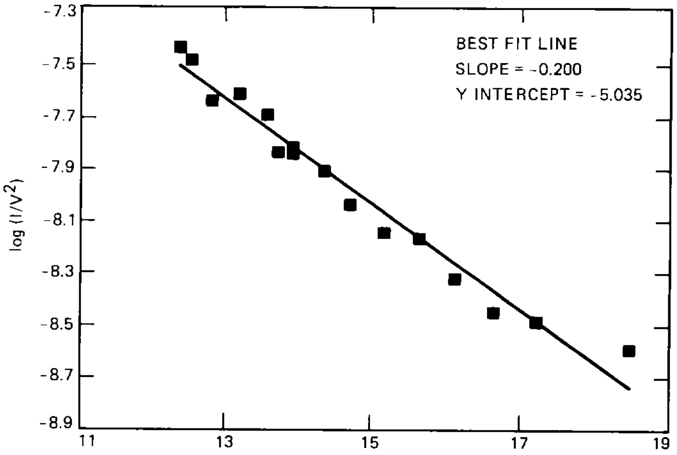

Fig. 6. Fowler–Nordheim plot of cathode total current and applied voltage (helium background pressure of 1E-5 torr)