Stable field emission from W tips in poor vacuum conditions

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We report a stable field emission (FE) current from sharp tungsten (W) tips in relatively poor vacuum (up to 10^{-2} mbar) conditions. We use small tip–anode spacing to keep the extraction voltage low. A simple current regulator circuit, with a bandwidth of ~1.6 kHz, was designed, which controls the voltage applied according to the emission current measured. Without a current regulator circuit, an uncleaned W tip in unbaked 6×10^{-7} mbar system pressure cannot emit stable FE current and short-term fluctuations at a few nA current were found to be more than 300%. The current regulator circuit improves the FE current stability dramatically. It was observed that at current level of ~3.5 nA and regulation voltage of ~120 V the short-term fluctuations in the current were ~5% at 6×10^{-7} mbar unbaked system pressure. Subsequently, the system pressure was increased in steps up to 10^{-3} mbar of argon gas and it was observed that the current regulator circuit worked at almost the same efficiency. Around 10^{-2} mbar of Ar gas pressure larger short-term fluctuations started appearing and around 10^{-1} mbar of Ar gas pressure the current regulator circuit failed to regulate the current. In another experiment, at 10^{-3} mbar of Ar gas pressure, at ~1.5 and 25 nA current levels long-term FE current stability was recorded. Our results show that the FE current stability in our experiments is much better than that reported in the literature with feedback on the tip–anode distance. This study may find applications in focused electron beam systems as well as in electron impact ion sources. [DOI: 10.1116/1.1575760]

I. INTRODUCTION

The history of the development of cold field electron emitters for industrial application shows that achieving better current stability in relatively poor vacuum conditions is one of the big challenges that remains as yet unsolved.[1–3] The nature of field emission (FE) current fluctuations has been well studied by various researchers (see Refs. 4 and 5, and references therein). Tungsten field emitters were widely studied by Dyke and co-workers and they concluded that for their stable operation 10^{-12} Torr system pressure (ultrahigh vacuum) is needed, which is not practical in commercial devices.[2,6] The conditions for a stable FE current for fixed applied voltage are well known.[2] First of all, there should not be any change in the work function of the emitter material. In recent years, there has been a considerable amount of research on different materials such as diamond thin films and carbon nanotubes, which are more chemically inert than metal and are potential candidates for FE cathodes.[1,3] Despite considerable progress for these new materials, they do not exhibit excellent FE current stability.[1,7–10] Second, the shape of the emitter tip should be constant at the atomic scale during emission. Since positive ion bombardment of the tip is one of the main causes for FE current instability,[2] we believe that the device must be operated at voltages less than the first ionization potential of ambient gas molecules. But even then the FE current may not be stable.[11] Therefore, we believe that for the ultimate success of FE based devices, it is not going to be enough to rely only on new materials which are just better than metal emitters. Instead, it seems that there should be some active mechanism in devices which corrects and controls the voltage applied to stabilize the FE current. This idea is not new because a feedback mechanism to stabilize near-axial emission was applied by Cleaver and Smith[12] in a scanning electron microscope. Kanemaru *et al.*[13] showed that stable emission at pressures up to 10^{-5} Torr can be achieved by metal–oxide–silicon field-effect-transistor (MOSFET)-structured silicon field emitters, which was not possible with conventional silicon FE tips. There were many attempts by Baptist and co-workers to use a resistance sheet as a passive element to improve FE current stability.[14,15] However, it did not turn out to be a final solution. Py and Baptist have shown the problems with a resistive sheet and recommended avoiding it as much as possible.[14] There was an excellent effort by Chang and co-workers to use feedback on the tip–anode distance to improve FE current stability.[16–18]

In this article we present our initial results of a FE current stability study on tungsten emitters held within a few tens of micrometers from a counterelectrode in poor vacuum conditions (in Ar gas). A simple current regulator circuit is used to correct and control the voltage applied according to the measured output of FE current. The bandwidth of this feedback can be significantly higher than the feedback on the tip–anode distance[16] to maintain constant FE current.

The main goal of this study was to develop stable field emitters at poor vacuum conditions. Such sources may find application in focused electron beam systems as well as in electron impact ion sources.

II. EXPERIMENT

Sharp single tungsten (W) FE tips were prepared from W wire of 0.16 mm diameter by electrochemical etching in 3 N

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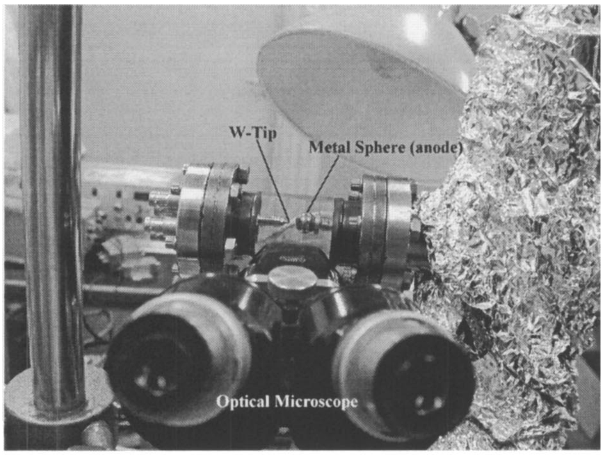
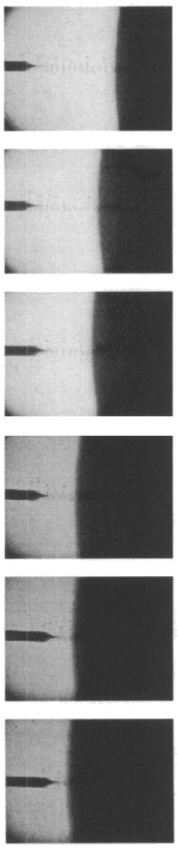


(a)



(b)

FIG. 1. (a) Photograph of (i) FE tube (that contains tip–metal sphere assembly) attached to a high vacuum system and (ii) optical microscope ($M=50$) to view the spacing between the tip–metal sphere. (b) Displacement of the anode to adjust the spacing of the W tip and anode (the photographs were taken through an optical microscope).

NaOH solution. Details of the procedure for making sharp W tips can be found elsewhere.[19,20] A scanning electron microscope (Philips XL30S) was used to determine the radius of the W tips.

FE measurements were carried out in a glass tube [see Fig. 1(a)] attached to a high vacuum system. The high vacuum system consists of a diaphragm vacuum pump, turbomolecular pump, convectron gauge, cold cathode gauge, and a precision leak valve to pass argon (Ar) gas in the system. A gold-coated stainless steel sphere (diameter of ~1 cm) was used as a counterelectrode, which could manually be moved with 20 μm precision towards the tip to adjust the spacing between the W tip and the anode [see Fig. 1(b)]. The tip–sphere spacing could be directly observed through the glass tube [see Fig. 1(a)] using an optical microscope with magnification of 50×. The current stability measurements were carried out using a high voltage power supply and a digital oscilloscope and homemade current regulator circuit (bandwidth of ~1.6 kHz). A schematic of the current regulator circuit attached to the experimental setup is shown in Fig. 2. The current regulator circuit can be used up to 500 V tip voltage. In the experiments presented here, W tips were used which emit a few nanoamps around 120 V, with electrode spacing of ~60 μm. The FE current stability experiments were performed in unbaked 6×10^{-7} mbar system pressure, without and with the current regulator circuit. Subsequently, using Ar gas, the system pressure was increased step by step up to 10^{-1} mbar to see the current regulating action of the circuit. In another experiment, at 10^{-3} mbar of Ar gas pressure, at ~1.5 and 25 nA current long-term FE current stability was recorded.

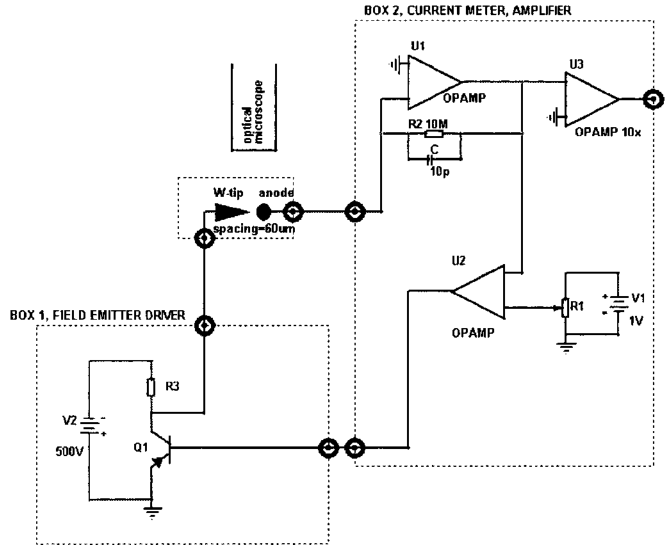


FIG. 2. Schematic of the current regulator circuit attached to the FE tube.

III. RESULTS AND DISCUSSIONS

The tungsten tips used in the experiments were not cleaned or flashed before or during the experiment. It was found that tip radii of typically 10–15 nm (see Fig. 3) can emit a few nanoamps around 120 V at 60 μm electrode spacing that have more than 300% fluctuation in current. Then, the current regulator circuit was connected to the tip and counterelectrode. It improved the FE current stability dramatically. It was observed that at current level of ~3.5 nA and regulation voltage of ~120 V, the fluctuations in the FE current were ~5% [see Fig. 4(a)]. After more than 1.5 h, stable operation of the W FE tip was recorded [see Fig. 4(b)]

FIG. 3. Typical scanning electron micrograph of one of the W tips which was used in this study.

in this experiment before measuring the short-term stability at different Ar gas pressures. We emphasize here that with a W FE tip at this pressure, it is impossible to achieve FE current stability without a current regulator circuit. The current regulating action can be seen clearly in Fig. 4(b) in the time interval from 60 to 80 min, when the current tries to increase due to some unknown change on the tip surface that causes the current regulation circuit to lower its voltage in order to maintain constant FE current.

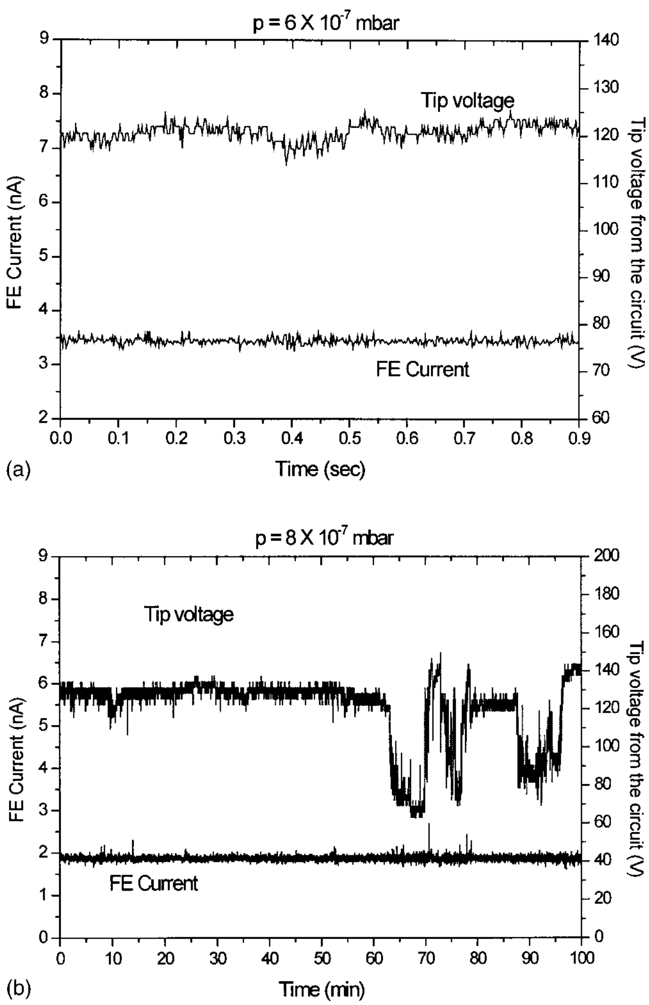


FIG. 4. (a) Short-term FE current stability and tip voltage fluctuations at unbaked 6×10^{-7} mbar. (b) Long-term FE current stability and tip voltage fluctuations at unbaked 8×10^{-7} mbar.

Subsequently, the system pressure was increased up to 10^{-3} mbar of Ar gas and it was observed that the current regulator circuit worked with almost the same efficiency as that shown in Figs. 5(a)–5(c). Around 10^{-2} mbar of Ar gas pressure larger short-term fluctuations started appearing [see Fig. 5(d)]. It can clearly be seen in Fig. 5(d) that for every jump in current there is a corresponding decrease in tip voltage within the response time (~1.6 kHz bandwidth) of the circuit. This nicely shows the regulating action of the current regulator circuit. By decreasing the time constant of the current regulating circuit the current jumps might be kept smaller and result in a more stable FE current even at high pressures. Around 10^{-1} mbar of Ar gas pressure the current regulator circuit failed to regulate the current.

In another experiment, at 10^{-3} mbar, at an ~1.5 nA FE current level and W-tip voltage of ~70 V, more than 40 h of stable FE was recorded over a period of four days [see Fig. 5(e)]. It was observed that after switching off the emission current at night, it returns to the same value when switched on the next morning. Figure 5(e) shows that the tip voltage slowly decreased, perhaps due to sharpening of the tip radius by ion bombardment,[21] until the FE current stability experiment was stopped after four days.

At higher current levels, ~25 nA and W-tip voltage of ~80 V, at 10^{-3} mbar, almost one week of stable FE was recorded [see Fig. 5(f)]. Large fluctuations in voltage were observed. It is believed that the tip went through cyclic changes and became sharp and blunt several times[21] until the experiment was stopped on the seventh day. However, the continuous drop in voltage observed in Fig. 5(e) was not observed. We suspect that the initial field emitter shape and the value of the FE current drawn may play an important role here. Even more FE current (a few hundred nanoamps) from a tungsten tip can be drawn if the tip–anode spacing is decreased to a submicron scale,[16] which was not possible in the present experimental setup.

These experimental results show that the FE current stability in poor vacuum can be much better than that reported in the literature.[16,17] These studies were performed with a tip in front of an anode that stopped the beam. For practical application, we will often need to form a beam behind the anode. From many studies, it is known that a micron-sized aperture can be placed within a micron of the tip. For very sharp tips and small tip–anode spacing, the anode voltage can be lower than the first ionization potential of gas molecules.[11] Fluctuations in electron energy due to changes in tip voltage are often not desirable. Although we believe that, if we operate a FE tungsten tip below the first ionization potential of Ar gas, smaller voltage fluctuations will occur because sputtering due to ion bombardment is avoided, and voltage fluctuations due to surface phenomena like adsorption, desorption, and surface diffusion are unavoidable. However, if the feedback is on the anode voltage there is no electron energy fluctuation.

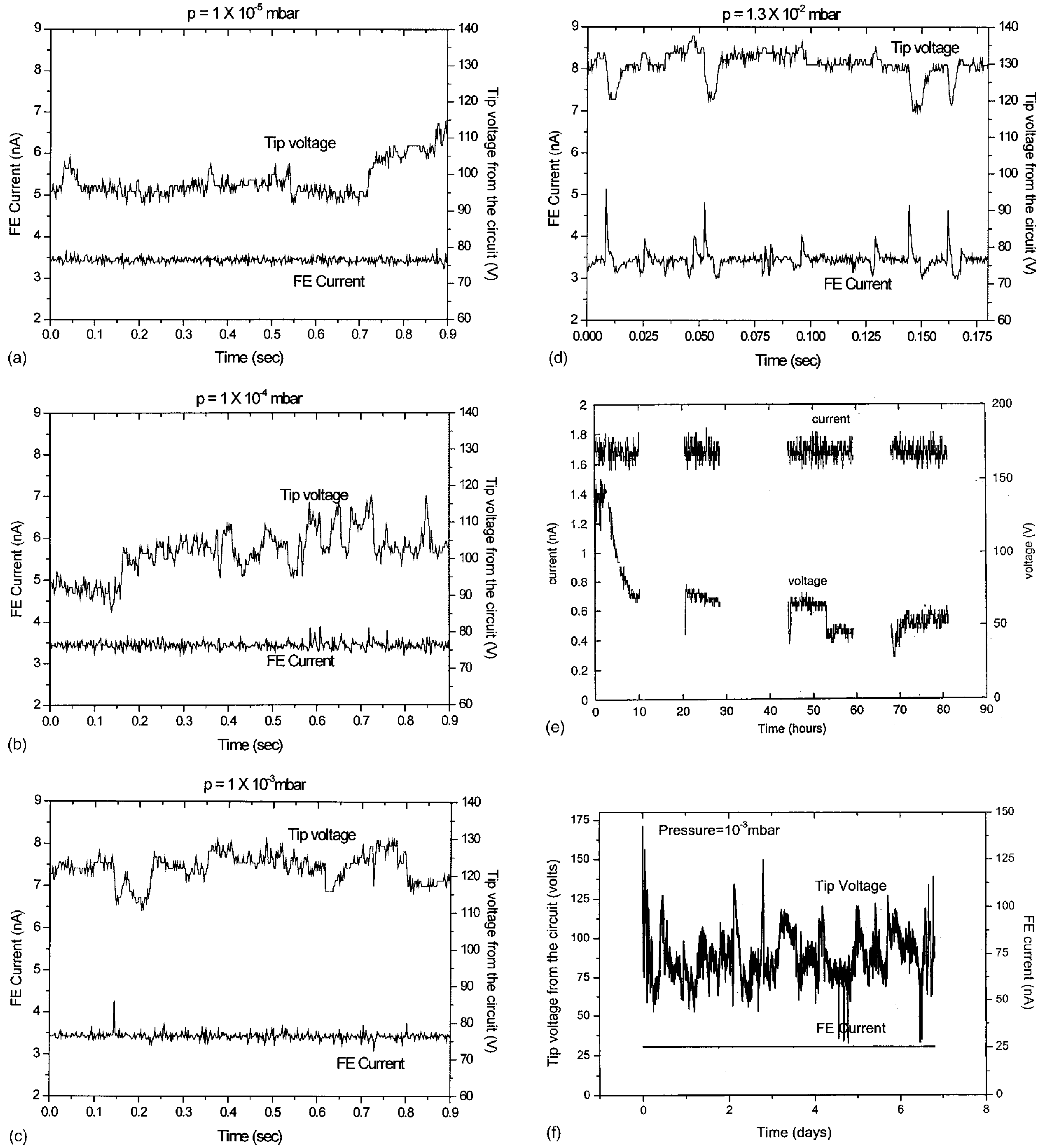


FIG. 5. (a)–(c) Short-term FE current stability and tip voltage fluctuations at unbaked 10^{-5}, 10^{-4}, and 10^{-3} mbar, respectively. (d) Short-term FE current stability and tip voltage fluctuations at 1.3×10^{-2} mbar. (e) Long-term FE current (~1.5 nA) stability and tip voltage fluctuations at 10^{-3} mbar. (f) Long-term FE current (~25 nA) stability and tip voltage fluctuations at 10^{-3} mbar.

The small unavoidable change in voltage at the anode in such a system would obviously lead to fluctuation of the virtual source size, which is highly undesirable. However, a second electrode can compensate for the lens effect of the voltage change at the anode. This should not be too difficult at low voltage.

One should realize that with feedback on the total emission current, it is only the total current which is being stabilized. It is expected that the angular distribution of the current can still show large fluctuations. Thus, if one uses an apertured beam like that in an electron microscope, the current within that aperture is not expected to be stable. In order to obtain a stable beam one needs to feedback on the apertured current itself or perhaps on the current emitted in a narrow ring around the aperture as proposed in Reference 22.

The extreme example of field emission at high pressure and small extraction voltage is found in scanning tunneling microscopes at atmospheric pressure. This leads us to expect that we have not yet reached the highest pressure at which stable emission is possible.

IV. CONCLUSIONS

We have shown that tungsten field emitters in close proximity to the extraction electrode have current stability better than 5% using a current regulator circuit at Ar gas pressure up to 10^{-3} mbar. At low pressures, the stability is significantly better than that reported for feedback on the tip–anode distance. Experiments are in progress to work with lower tip voltage (~10–15 V), smaller cathode–anode spacing (submicron), and higher bandwidth (~100 kHz) of the circuit. It might improve current stability even at higher pressures.

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