Carbon-Nanotube Cold Cathodes As Non-Contact Electrical Couplers

Y. Chen, C. Liu, and Y. Tzeng

Department of Electrical and Computer Engineering

Auburn University, Auburn, Alabama 36849 (USA)

Abstract

When two carbon-nanotube coated electrodes are placed at a small distance from each other, electron field emission from carbon nanotubes allows DC or AC electrical current to flow between these two electrodes. The voltage drop across these two electrodes depends on the electric field needed for field emission of electrons for carrying the electrical current in the circuit and the distance between these two electrodes. For applications to high-voltage circuits, which operate at much higher voltages than what is needed across two counter electrodes to provide adequate electron field emission current, this device serves as an effective non-contact electrical power coupler. Both rectifying electrical coupling and full-wave electrical coupling have been explored and will be reported in this paper.

* Corresponding author's e-mail address: tzengy@eng.auburn.edu

1. Introduction

Carbon nanotube is among the most promising cold cathode materials because of its excellent electrical, thermal, and mechanical properties, such as high aspect ratio, high mechanical strength, and high resistance to chemical and physical attacks [1-5]. Low threshold electric field and turn-on electric fields for field emission of electrons, as well as high emission current densities have been demonstrated. In this paper, carbon nanotube cold cathodes were used as high-voltage rectifiers and full-wave non-contact power couplers. For these applications cold cathodes with high electron field emission current densities and low turn-on electric fields are desirable. The smaller the voltage drop across the electrodes and the larger the current allowed per square centimeter of the electrode surface area, the better the device is for non-contact electrical power coupling.

2. Experimental details

2.1. Fabrication of carbon- nanotube coated electrodes

Iron catalyst was sputtered on silicon substrates followed by heating in air at 300ºC for 8 hours. Thermal CVD of carbon nanotubes was performed in a vacuum furnace filled with a gas mixture of acetylene and argon at a pressure of 70 torr. The flow rates for argon and acetylene were 75 sccm and 20 sccm, respectively. Before the gas mixture was fed into the furnace, the substrate was heated to 700ºC in vacuum and the temperature remained constant during the 20 minutes growth of carbon nanotubes [6]. Besides multi-wall carbon nanotubes grown by thermal CVD on silicon substrates, commercially available single-wall carbon nanotubes were also used to coat on silicon substrates[7].

For full-wave AC power coupling, both electrodes were coated with carbon nanotubes. For rectifying electrical power coupling, uncoated and clean silicon substrates, instead of carbon nanotube coated substrates, were used as the anode while a carbon-nanotube coated electrode was used as the cathode.

2.2. Current-electric field characteristics measurement

When DC electron field emission characteristics, i.e. the electron field emission current versus the applied electric field , were measured, an electrically insulating spacer was placed between the uncoated and clean silicon, which served as the anode, and a carbon-nanotube coated electrode, which served as the cathode. A computer controlled DC power supply was applied to allow electron field emission current to flow through the vacuum gap and then through a current-limiting resistor to complete the circuit loop. A pico-ammeter was used to measure the electron field emission current with measured data being fed to a computer for further processing. The electrodes were placed inside a high-vacuum chamber for electron field emission measurements.

Shown in Figure 1 are the schematic diagrams for the experimental setups for the rectifying and the full-wave power coupling experiments. A 60 Hz AC voltage was applied across a current-limiting resistor and two electrodes, as shown in Figure 1. The voltage waveform for the voltage across these two electrodes and the voltage waveform across the current-limiting resistor, were recorded using an oscilloscope and two voltage probes. The electron field emission current is equal to the voltage across the current limiting resistor divided by the resistance of this resistor. For rectifying operation, one electrode was coated with carbon nanotubes while an uncoated and clean silicon electrode was used as the counter electrode. For full-wave coupling of AC electrical power, both electrodes were coated with carbon nanotubes.

3. Results and discussion

3.1. Rectifying electrical power coupling

When electrical current is allowed to flow only in one direction, a carbon-nanotube coated electrode was used as the cathode while an uncoated and clean silicon substrate was used as the anode. A 60 Hz AC power supply was applied to the circuit.

3.1.1. Single-wall carbon- nanotube coated cathodes

Shown in Figure 2 (a) is the oscilloscope trace representing a half-wave rectified 60 Hz electron field emission current that flowed across a vacuum gap between a single-wall carbon-nanotube coated cathode and a uncoated and clean anode. An AC voltage with peak voltage of 606 volts was applied. There was no electron field emission from the clean silicon because the applied electric field was below the threshold voltage needed for electron field emission from the clean silicon surface.

After a few minutes, as shown by the oscilloscope traces in Figure 2 (b-d), field emission of electrons originated from the originally uncoated and clean silicon electrode and flowed across the vacuum gap towards the carbon-nanotube coated electrode. Electrons originating from the clean silicon electrode is represented in Figure 2 by the negative part of the waveforms with a smaller amplitude than the positive part of the waveforms. Electron field emission from the originally uncoated and clean silicon electrode increased with time at the beginning of the operation. After several hours of operation, both the electron current originated from carbon-nanotube coated electrode and that from the uncoated silicon electrode became smaller and finally became stabilized as shown in Figure 2(d).

The on-set of electron field emission from the originally uncoated and clean silicon electrode was caused by the coating of debris that originated from the carbon-nanotube coated electrode and were forced to fly from the carbon-nanotube coated cathode across the vacuum gap to the originally clean silicon electrode.

Shown in Figure 2(e) are the electron field emission characteristics of a single-wall carbon-nanotube coated electrode. The dotted curve and the circled curve represent the electron field emission characteristics corresponding to the increasing and the decreasing applied electric fields, respectively. After the previously described operation, the electron field emission characteristics of the originally clean silicon electrode changed from originally having no electron field emission within the range of applied electric field to what is shown in Figure 2 (f). The dotted curve and the circled curve represent the characteristics corresponding to the increasing and the decreasing applied electric fields, respectively. When a negative voltage was applied to the carbon-nanotube coated electrode with respect to the originally clean silicon electrode, some loose or break-away carbon nanotubes flew across the gap and became deposited on the originally clean silicon electrode. After the deposition of carbon nanotubes on the originally clean silicon electrode, the on-set electric field for electron field emission from this electrode became similar to that for the original single-wall carbon-nanotube coated electrode. This indicates that some broken pieces or loose single-wall carbon nanotubes on the cathode that was originally coated with carbon nanotubes were forced by the electric field to fly and coated onto the originally clean and uncoated silicon substrate. This process made the originally clean and uncoated silicon behave like the silicon electrode that was originally coated with single-wall carbon nanotubes.

3.1.2. Multiple-wall carbon-nanotube coated cathodes

Shown in Figure 3 (a) is the oscilloscope trace of a half-wave rectified 60 Hz electron field emission current that flowed through the gap between a multiple-wall carbon-nanotube coated cathode and an originally uncoated and clean anode after an AC power supply with a peak voltage of 606 volts was turned on. There was no electron field emission from the clean silicon.

After four hours of operation, there was still no electron emission from the clean silicon electrode as shown in Figure 3(b). This indicates that the adhesion of CVD multiple-wall carbon nanotubes on the substrate was stronger than that of single-wall carbon nanotubes coated on the substrate. The applied voltage was raised from 606 volts to 2373 volts. Almost immediately after the voltage was increased, the waveform shown in Figure 3(c) showed electron field emission current flowing in both directions from both the originally clean silicon electrode and the original carbon-nanotube coated electrode. It took 2372 volts applied voltage instead of just 606 V to break loose pieces of carbon nanotubes and possibly some other non-nanotube carbon species from the CVD carbon-nanotube coated electrode. The electron field emission from the silicon electrode remained stable for three hours as shown in Figure 3(d)

The on-set of electron field emission from the originally clean silicon electrode, that was not intentionally coated with carbon nanotubes, was caused by the coating with carbon nanotubes and non-nanotube carbon species that were forced to fly from the carbon-nanotube coated cathode to the clean silicon electrode by a strong electro-static force.

Shown in Figure 3(e) are the electron field emission characteristics of the electrode that was originally coated with multiple-wall carbon nanotubes. Shown in Figure 3(f) are the electron field emission characteristics of the originally uncoated and clean silicon electrode after applying 2373 volts of 60 Hz AC across the electrodes and a current limiting resistor. The turn-on electric field for electron field emission from the clean silicon electrode was higher than the originally CVD coated electrode. This indicates that some non-nanotube carbon species were forced to leave the original carbon-nanotube coated electrode to deposit on the originally clean silicon. These non-nanotube carbon species required a higher electric for the on-set of electron field emission than that for the original thermal CVD carbon-nanotube coated electrode.

3.2. Full-wave non-contact power coupling

For applications to full-wave non-contact power coupling, both electrodes were coated with carbon nanotubes so that electron current can flow in both directions.

3.2.1. Single-wall carbon-nanotube coated full-wave couplers

Shown in Figure 4 are two oscilloscope traces for the applied sinusoidal voltage and the electrical current caused by electron field emission from both electrodes. One of these two electrodes had a higher electron field emission current density than the other one. This caused the waveform of the electrical current to become non-symmetrical.

3.2.2. Multiple-wall carbon- nanotube coated full-wave couplers

Shown in Figure 5 (a-d) are four oscilloscope traces for the electron field emission current flowing through the gap between two electrodes coated with CVD multiple-wall carbon nanotubes. The electrical power could be coupled in both directions. As shown in Figure 5 (d), the electron field emission current actually increased with time of operation as compared with what is shown in Figure *5* (a). Strong electric fields between two electrodes forced loose or broken carbon species including nanotubes to fly from one electrode to the other. These small pieces are the cause of the increasing electron field emission current with time. The exposure of carbon nanotubes to bombardment by electrons from the counter electrode reduced the adsorption of residual gas molecules on carbon nanotubes and may also have contributed to the increasing electron emission current density with time. Shown in Figure 6 are the electron field emission currents from these two electrodes as a function of time. Figure 6 shows that the electron field emission currents increased with time of operation.

3.3. Potential applications of carbon-nanotube power couplers as vacuum opening and closing switches

When the effective electrical coupling resistance is minimized, the electrical couplers may serve as high-voltage electrical switches. When the applied voltage is much higher than the voltage across the vacuum gap between these two electrodes, these two electrodes behave like a closed switch. This switch is useful for high voltage circuits that operate in space or in vacuum. This switch can also be opened by increasing the distance between two carbon-nanotube coated electrodes until the applied voltage is too low for electron field emission from carbon-nanotube coated electrodes. A properly patterned carbon-nanotube coated electrode and a patterned carbon-nanotube coated counter electrode can also move with each other in parallel in such a way as to increase the distance between a patterned carbon-nanotube coating on one electrode with respect to another patterned carbon-nanotube coating on the counter electrode. When the distance between two carbon-nanotube coated electrodes is larger than the minimum distance at which the applied electric field starts to induce electron field emission, the coupling of electrical power stops and the switch is effectively opened.

4. Conclusions

Applications of carbon-nanotube coated electrodes as rectifiers and full-wave non-contact electrical power couplers have been explored and reported. Good adhesion of carbon nanotubes to the cathode is critical for the rectifying application. Unless the anode can be protected from unwanted carbon species and loose or break-away carbon nanotubes that are attracted to the anode by strong electric fields, the anode will be coated with these carbon species and will not be able to sustain a strong negative voltage without the undesirable electron field emission originating from the contaminated anode. For full-wave power coupling, the cross contamination and bombardment by electrons from counter electrodes did not reduce the electron field emission current.

References

[1] Yahachi Saito and Sashiro Uemura: “Field emission from carbon nanotubes and its application to electron sources”, Carbon, 85, 7, 2000, p169.

[2] W. Zhu et al.: “Large current density from carbon nanotube field emitters”, Appl. Phys. Lett., 75, 6, 1999, p873.

[3] O. Gröning et al.: “Field emission properties of carbon nanotubes”, J. Vac. Sci. Technol. B, 18(2), 2000, p665.

[4] R. Saito, G. Dresselhaus, and M. S. Dresselhaus: Physical Properties of Carbon Nanotubes, Imperial College Press, London, 1999 Journal of Applied Physics, Volume 85, Number 7, 1999, p3832.

[5] Kenneth A. Dean and Babu R. Chalamala: “Field emission microscopy of carbon nanotube caps”, J. Appl. Phys., 85, 7, 1999, p3832.

[6] S. Fan, M.G. Chapline, N.R. Franklin, T.W. Tombler, A.M. Cassell, and H. Dai, “Self-Oriented Regular Arrays of Carbon Nanotubes and Their Field Emission Properties,” Science, 22 January 1999, Vol. 283, p.512.

[7] Y. Tzeng, Y. Chen, and C. Liu, " Fabrication and characterization of non-planar high-current-density carbon-nanotube coated cold cathodes," Diamond and Related Materials, accepted for publication, Oct 5, 2002.

Figure Captions:

Figure 1. Schematic diagrams of experimental setups used for measuring voltage-current characteristics of rectifying power couplers and full-wave power couplers.

Figure 2. Electron field emission characteristics of single-wall carbon nanotubes: (a) Rectifying electron field emission current immediately after the applied voltage was turned on. (b) After 15 minutes operation. (c) After 2 hours operation. (d) After 16 hours operation. (e) Current-electric field characteristics for the carbon-nanotube coated cathode. The dotted curve and the circled curve represent electron field emission currents corresponding to an increasing and decreasing applied electric field, respectively. (f) Current-electric field characteristics for the originally uncoated and clean silicon electrode after electron field emission operation. The dotted curve and the circled curve represent electron field emission currents corresponding to an increasing and decreasing applied electric field, respectively.

Figure 3. Electron field emission characteristics of multiple-wall carbon nanotubes: (a) Rectifying electron field emission current immediately after the applied voltage was turned on. (b) After 4 hours operation. (c) Applied voltage was increased from 606 volts to 2373 volts. (d) After 3 hours operation at 2373 volts. (e) Current-electric field characteristics for the multiple-wall carbon-nanotube coated cathode. The dotted curve and the circled curve represent electron field emission currents corresponding to increasing and decreasing applied electric fields, respectively. (f) Current-electric field characteristics for the originally uncoated and clean silicon electrode after the electron field emission operation. The dotted curve and the circled curve represent electron field

emission currents corresponding to increasing and decreasing applied electric fields, respectively.

Figure 4. Electrical power coupling between two silicon electrodes both coated with single-wall carbon nanotubes.

Figure 5. Electrical power coupling between two silicon electrodes both coated with multiple-wall carbon nanotubes: (a) Electron field emission current when the power supply of 1193 volts was first turned on. (b) After 25 minutes operation. (c) After 2 hours and 30 minutes operation. (d) After 9 hours operation.

Figure 6. Electron field emission current from both carbon-nanotube coated electrodes powered by 1193 volts AC voltage showing increasing electron field emission currents with time. These two electrodes have different electron field emission current densities.

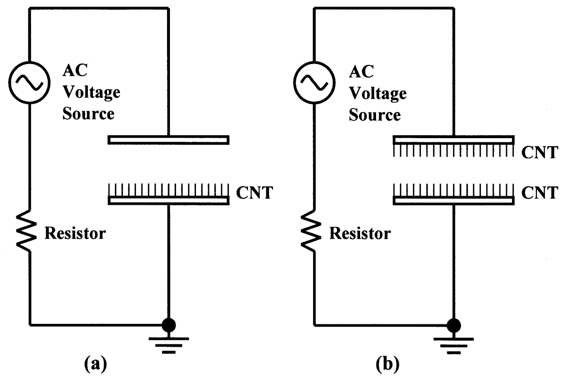

Figure 1. Schematic diagrams of experimental setups used for measuring voltage-current characteristics of rectifying power couplers and full-wave power couplers.

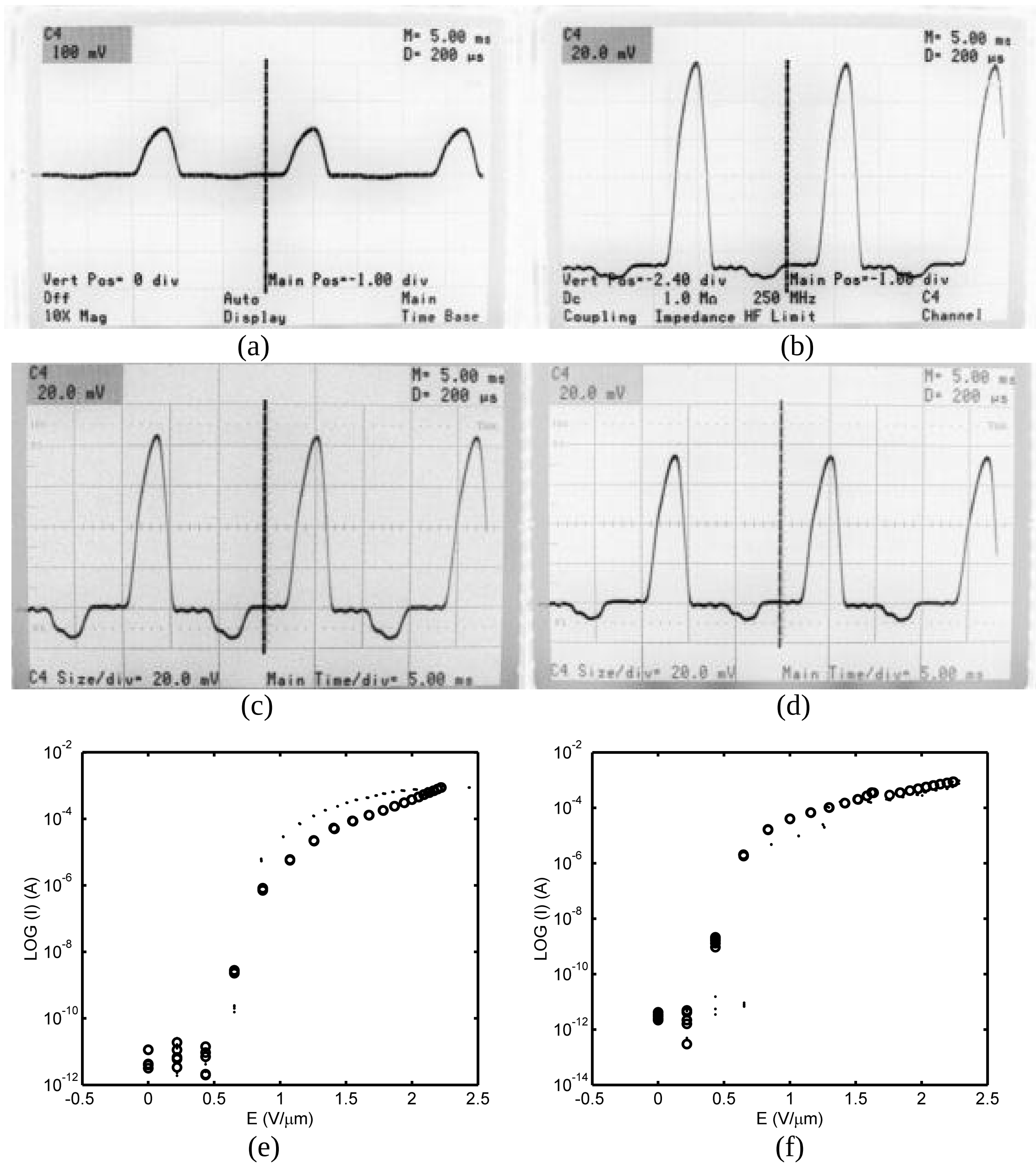

Figure 2. Electron field emission characteristics of single-wall carbon nanotubes: (a) Rectifying electron field emission current immediately after the applied voltage was turned on. (b) After 15 minutes operation. (c) After 2 hours operation. (d) After 16 hours operation. (e) Current-electric field characteristics for the carbon-nanotube coated cathode. The dotted curve and the circled curve represent electron field emission currents corresponding to an increasing and decreasing applied electric field, respectively. (f) Current-electric field characteristics for the originally uncoated and clean silicon electrode after electron field emission operation. The dotted curve and the circled curve represent electron field emission currents corresponding to an increasing and decreasing applied electric field, respectively.

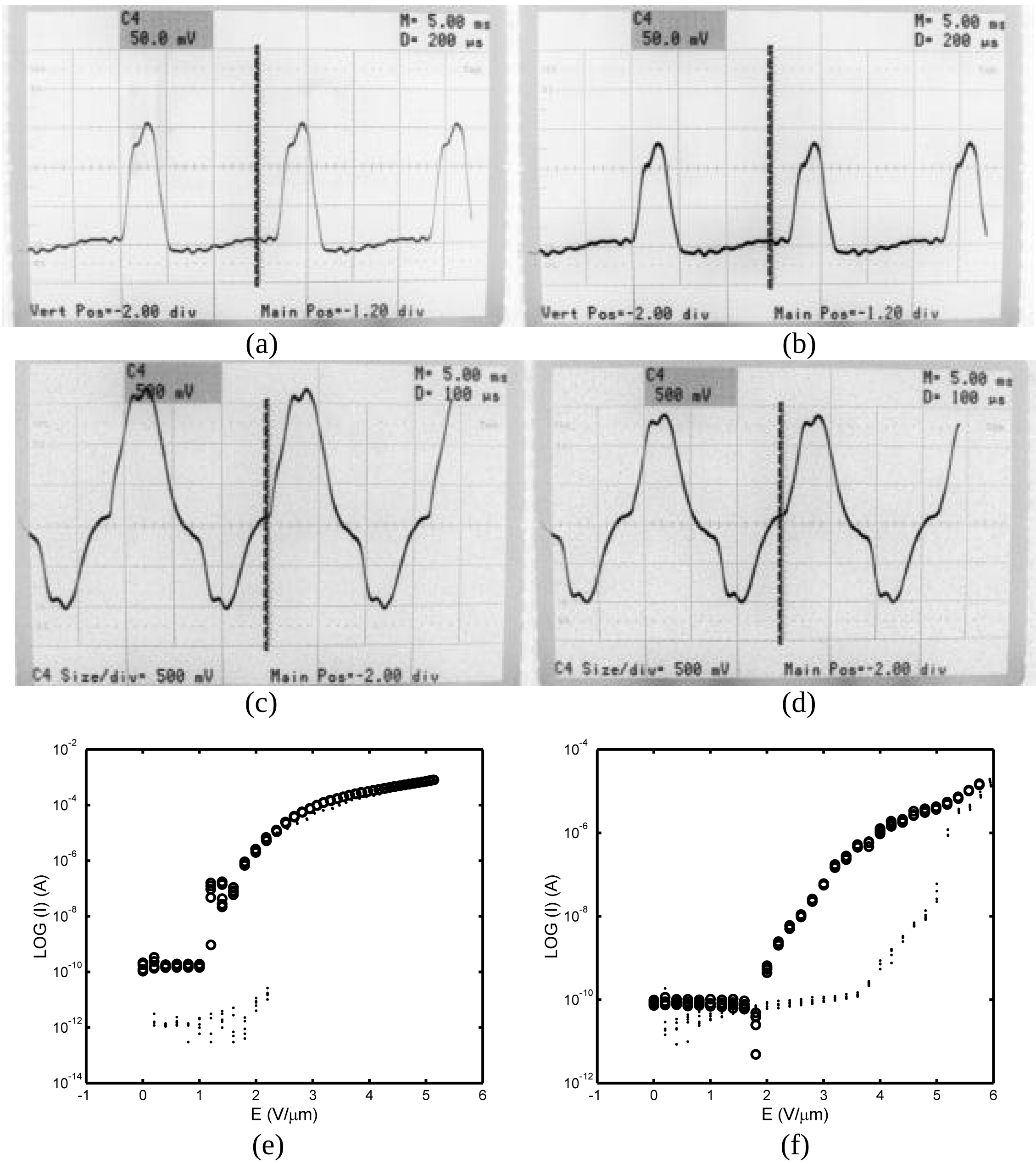

Figure 3. Electron field emission characteristics of multiple-wall carbon nanotubes: (a) Rectifying electron field emission current immediately after the applied voltage was turned on. (b) After 4 hours operation. (c) Applied voltage was increased from 606 volts to 2373 volts. (d) After 3 hours operation at 2373 volts. (e) Current-electric field characteristics for the multiple-wall carbon-nanotube coated cathode. The dotted curve and the circled curve represent electron field emission currents corresponding to increasing and decreasing applied electric fields, respectively. (f) Current-electric field characteristics for the originally uncoated and clean silicon electrode after the electron field emission operation. The dotted curve and the circled curve represent electron field emission currents corresponding to increasing and decreasing applied electric fields, respectively.

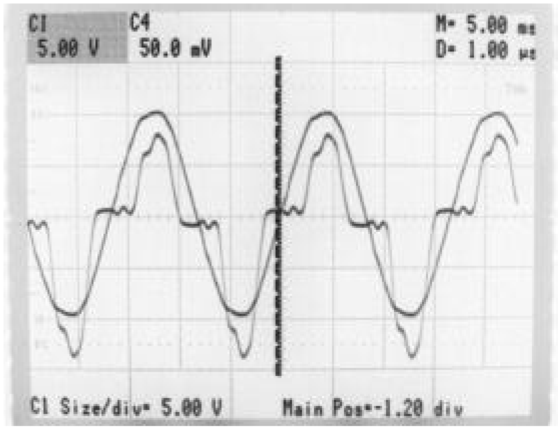

Figure 4. Electrical power coupling between two silicon electrodes both coated with single-wall carbon nanotubes.

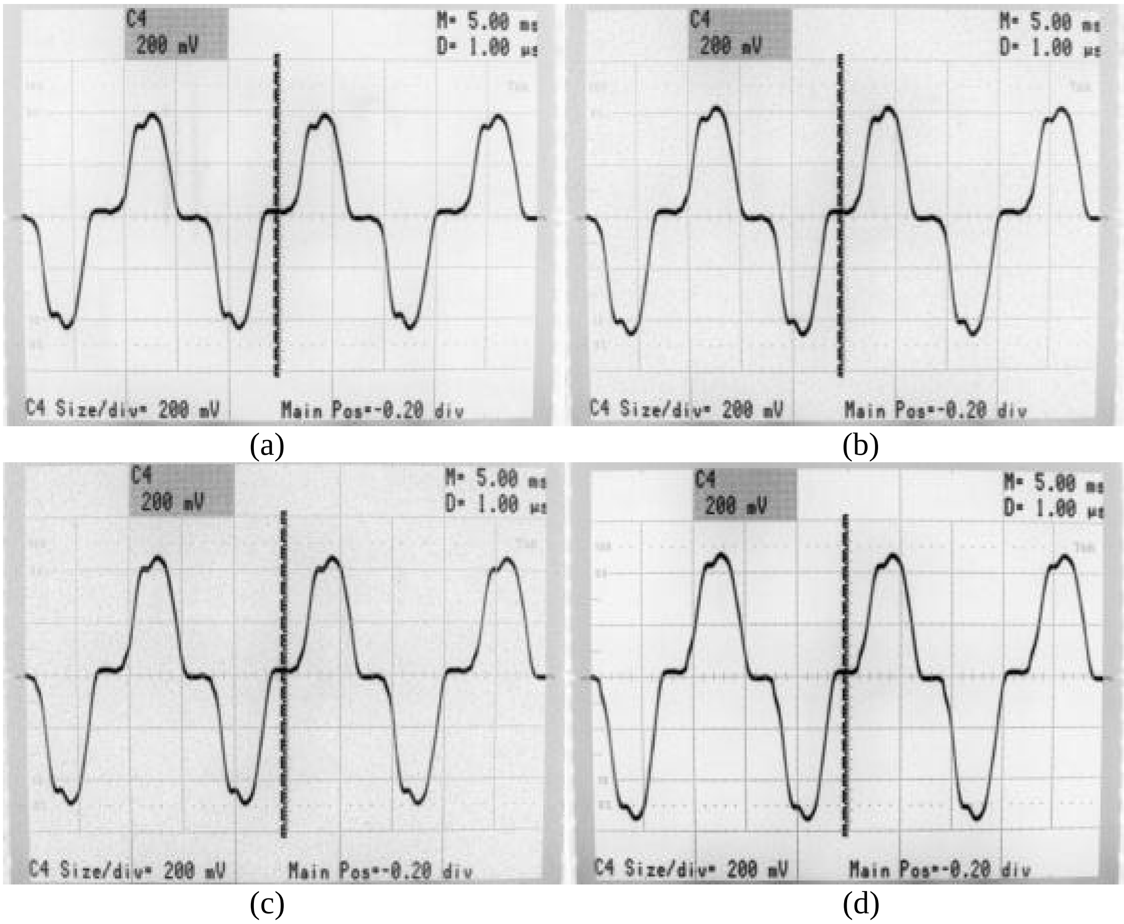

Figure 5. Electrical power coupling between two silicon electrodes both coated with multiple-wall carbon nanotubes: (a) Electron field emission current when the power supply of 1193 volts was first turned on. (b) After 25 minutes operation. (c) After 2 hours and 30 minutes operation. (d) After 9 hours operation.

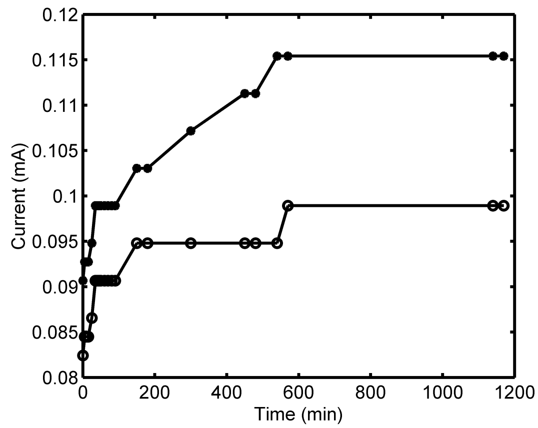

Figure 6. Electron field emission current from both carbon-nanotube coated electrodes powered by 1193 volts AC voltage showing increasing electron field emission currents with time. These two electrodes have different electron field emission current densities.