Final Report

High Density Magnetized Microdischarge Plasmas

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Synopsis

The focus of our prior research is on the understanding of the properties of *dc* - microdischarges in which *electrons are strongly magnetized, but ions are not*. The research is summarized by the papers/presentations listed at the end of this section [1-17]. The addition of a magnetic field to the otherwise non-magnetized discharges [1, 4, 12, 13] relaxes the usual *pd* scaling condition on the breakdown and sustain voltage in non-magnetized discharges due to the enhanced ionization coefficient through magnetic confinement of the electrons. The result of this confinement is that these microdischarges can be ignited and sustained at relatively low pressure, leading to conditions of very high electron temperatures, and very low electron/ion collisionality. The generation and operation of a magnetized microdischarge at low pressures and low power opened fields of applications that benefit from concentrated, high current density, and highly energetic ions. Below, we summarize some of our findings, including studies aimed at exploiting properties for applications demanding energetic ions. We also summarize our very recent progress on pulsed magnetized microdischarges at atmospheric pressure, for applications related to phase-change memory storage.

Studies of **E x B** Microdischarges at Low Pressure

During this grant, we have studied magnetized microdischarges with planar electrodes and non-uniform magnetic field configurations causing closed $\boldsymbol{E}\times\boldsymbol{B}$ electron drifts [5, 6, 10, 14, 16]. Figure 1 shows one of several electrode and magnetic field configurations studied. The magnetic circuit incorporates a SmCo permanent magnet together with a high purity iron core to form the poles. With this configuration, the magnetic field strength near the cathode is ~1 Tesla, resulting in an electron Larmor radius of 10 μm. A photograph of the plasma as seen through the transparent indium-tin oxide (ITO) anode is shown in Fig. 2. We see the annular shaped microdischarge, of scale less than ~1 mm, concomitant with where the transverse magnetic field is strongest. For applications related to displays or materials processing, we have studied the nature of the initial breakdown process [5, 6] and, in particular, the breakdown voltage requirements. Typical results are shown in Fig. 3 for discharge operation in argon. In the absent of magnetic field, the minimum in the breakdown voltage is expected to be close to 15 mm·Torr. We have carried out 1D Monte Carlo simulations [5] to confirm this minimum in the non-magnetized case and find good agreement with a secondary electron emission factor of $\gamma = 0.02$. The predicted breakdown characteristics using this MC simulation are also shown in Fig. 3. We see that with a magnetic field, there is a breakdown voltage

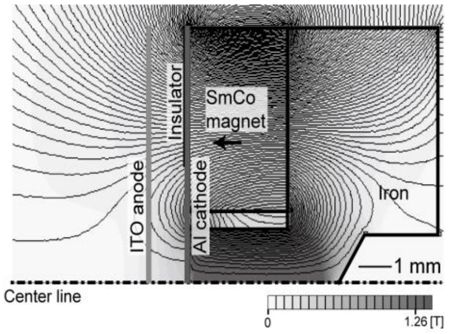


Figure 1. Schematic of the microdischarge with planar aluminum and ITO electrodes. The B-field is generated by the SmCo and iron poles behind the aluminum electrode, which serves as the discharge cathode.

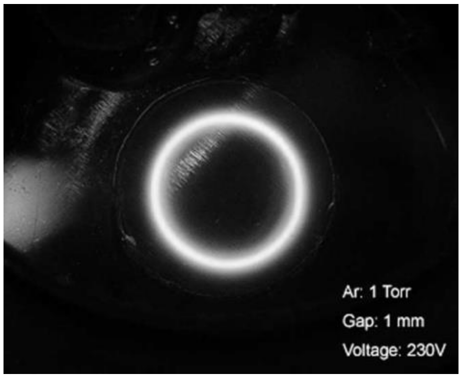


Figure 2. Photographic image of the magnetized microdischarge argon plasma as viewed through the indium-tin-oxide anode.

minimum in this range, due to the magnetic field non-uniformity and the presence of regions between the electrodes where the magnetic field is weak. More importantly, however, these magnetized microdischarges are found to have a *second minimum* [5, 6], seen here near a pressure of 1 Torr for argon, where the mean free path is about 300 μm. This minimum is an indicator that electrons are strongly magnetized, since the decrease in breakdown voltage is caused by the longer electron trajectory, resulting in a higher collision probability and an increased likeliness of an electron avalanche ionization cascade.

As mentioned above, the generation and operation of a microdischarge at low pressures and low powers opens up fields of applications that benefit from concentrated, high current density, and highly energetic ions. In this past two years, we have developed these discharges into energetic ion sources [2, 11] and micro-plasma thrusters for space propulsion [3, 8, 9]. As emphasized above, unique to the conditions of these magnetized microplasmas, the electrons are highly magnetized and ions are not necessarily magnetized (depending on ion mass) - a condition that can result in the generation of a high current density, high energy ion stream at low pressure. For the ion source studies carried out in our laboratory, the discharge is operated with an external cathode source to neutralize the resulting ion beam with electrons, and to produce relatively heavy ions ranging from argon to xenon, although in principal the source can be operated on a variety of inert and reactive gases, with lighter gases resulting in some ion magnetization (the subject of the proposed work). Figure 4 is a representative ion energy distribution, taken using a miniature retarding field analyzer, from the micro-ion source [2, 11] operating between 200 and 300 V. We see that the cathode/anode loss in these discharges is relatively low, with the peak ion energy falling within 90% of the applied potential.

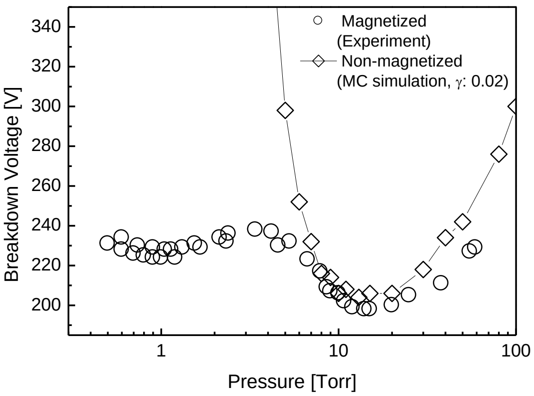


Figure 3. Breakdown characteristics of a magnetized microdischarge operating in pure argon. Also shown are results of MC simulations for the non-magnetized case.

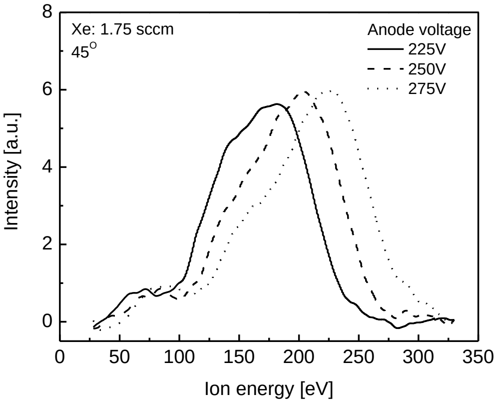


Figure 4. Typical ion energy distributions from the micro-ion source operating on Xe; anode voltage dependence on Xe flow rate of 1.75 sccm

Extensive studies have been carried out, in the use of a modified version of the micro-ion source, shown in the schematic in Fig. 5 (left), and photograph of Fig. 5 (right), as a potential space plasma propulsion device. These studies were carried out in vacuum facility specifically designed for evaluating the performance of these plasma thrusters [8, 9]. The background chamber pressure is maintained to better than 10^{-6} Torr with 2 sccm of Xe flow through the anode. Of course, the local discharge pressure in the ionization region near the discharge exit can be much higher (~10^{-3} - 10^{-2} Torr).

Figure 5. (left) Schematic illustration (right) Photograph of magnetized micro-plasma thruster.

This plasma thruster was operated at a power level as low as 10W, *one of the lowest powers achieved for **E** x **B** thrusters to date*, with a performance ranging from 10 – 16% thrust efficiency (see Fig. 6), and a specific impulse as high as 850 seconds [8,9]. This prototype thruster was initially water-cooled (Fig. 5a), although later analyses indicated that sufficient thermal control can be obtained by appropriate design of radiation surfaces. First designs also used an alumina cover over the central (iron) pole. We discovered that this central pole-piece was a source of thermal chocking, leading to very high temperature due to electron bombardment on the axis, where there is considerable ***B***-field convergence. Subsequent designs (e.g., that shown in the left of Fig. 5) incorporated thick (0.5 mm) polycrystalline diamond for heat spreading. The central dielectric (diamond) polepiece cover was found to greatly enhance the overall life of this miniaturized energetic plasma source under these extreme environments.

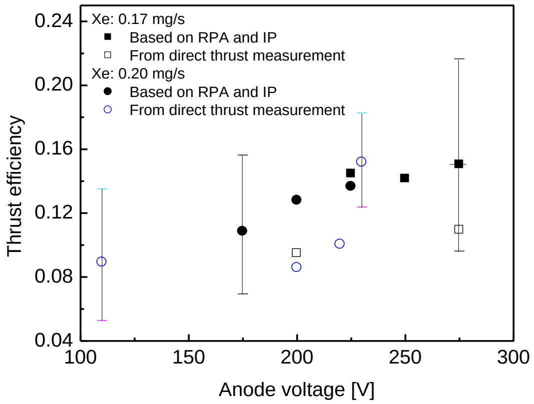


Figure 6. Performance of magnetized micro-plasma thruster.

Both the planar discharges, as well as the micro-ion sources, were found to exhibit considerable fluctuations in both discharge current and plasma properties. These disturbances are attributed to the growth of instabilities, not uncommon to low pressure magnetized discharges. That they are so prevalent in these microscale plasmas was somewhat surprising. *A detailed study of these instabilities and the associated turbulence is the subject of the proposed work* – a natural extension of our prior studies.

Studies of **E** ‖ **B** Microdischarges at Atmospheric Pressure

During this past three year period, we have also explored new, highly energetic states of microplasmas, with experiments carried out to understand the characteristics of *nanosecond pulsed*, high voltage, microdischarges in air under very *high reduced electric fields*. In the experiments that are described briefly below, which are still ongoing in our laboratory, we have generated reduced electric fields of $E/n = 10^{-14}$ V cm^2, values greater than those seen in typical low-pressure glow discharges, but at atmospheric pressure. The experiments were motivated by the potential applications of these discharges in through-wafer via etching in semiconductor fabrications, and also in phase-change memory devices. The broader concepts of such a device are depicted in Fig. 7. Experiments were conducted in ambient air, in the facility illustrated schematically in Fig. 8 (left) below. These experiments were motivated by this use of pulsed magnetized (or non-magnetized) microdischarges in phase change memory storage applications.

A 10 mm diameter tungsten wire, sharpened to a point of approximately 10-20 nm in radius by acid dip etching, served as a cathode point to plane (polished copper anode) discharge. With the copper anode grounded, the cathode was driven by a 15 ns duration, typically 2kV pulsed voltage from a high voltage pulsed power source (FID Technologies, Inc), capable of firing at rates as high as 100 kHz. Single pulse events were found to produce highly localized phase change features on the copper anode, often less than 1 μm in size (Fig. 8, top right), and sometimes as small as 100 nm in size. An unintensified CCD camera (averaging over 68 ms) was used to record discharge events, often averaged over many pulses. The photographs of discharges showed diffuse transient glows, typically comparable in width to the wire (10-20 μm in diameter). A photograph of the illuminated electrode configuration is also shown in Fig. 8, along with a representative optical microscope photograph of the resulting recorded phase-change feature (single plasma pulse) in polycrystalline copper. Very recent studies indicate that the presence of a magnetic field has only a weak affect (if anything, negative) on the stability of the plasma. Understanding the physics (and stability) of these microdischarges in electric fields that are parallel to strong magnetic fields continues to be the subject of ongoing work in our laboratory.

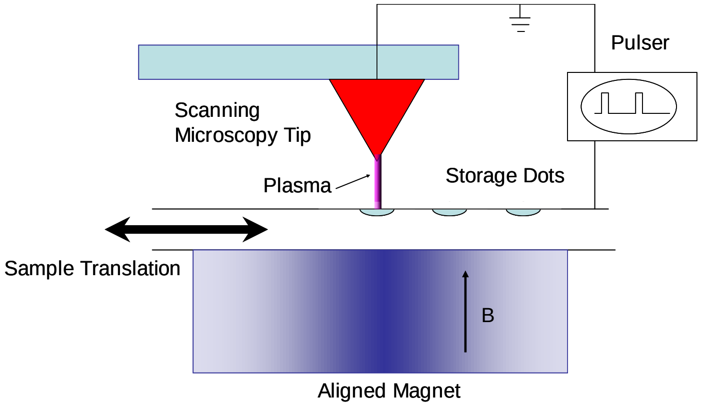
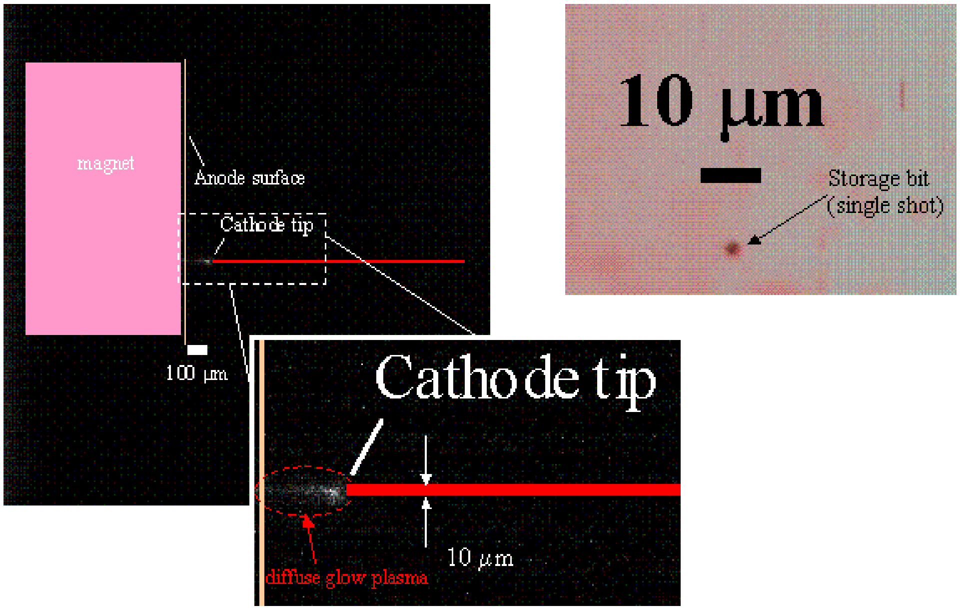


Figure 7. Schematic illustration of nanosecond pulsed micro-discharges at atmospheric pressure to produce nanoscale features on surfaces.



Publications Resulting from this Grant

(i) Archival Publications

[1] "Ion energy Distribution and Gas Heating in the Cathode Fall of a Direct-Current Microdischarge," T. Ito and M. A. Cappelli, Physical Review E **73**, 046401 (2006).

[2] "Low Power Magnetized Microdischarge Ion Source" T. Ito and M.A. Cappelli, Appl. Phys. Lett. **89**, 061501 (2006).

[3] "Experimental Characterization of a Micro Hall Thruster," T. Ito, N. Gascon, W. S. Crawford, and M. A. Cappelli, J. Propulsion and Power **23**, 1068-1074 (2007).

[4] "On the Production of Energetic Neutrals in the Cathode Sheath of Direct-Current Discharges," T. Ito and M.A. Cappelli, Appl. Phys. Lett. **90**, 101503 (2007).

[5] "Magnetized Microdischarge Plasmas in Low Pressure Argon and Helium," K. Kobayashi, T. Ito, M. A. Cappelli, and S. Hamaguchi, Journal of Physics: Conference Series **106**, 012020 (2008).

[6] "Magnetized Microdischarge Plasma Generation at Low Pressure," T. Ito, K. Kobayashi, S. Hamaguchi, and M. A. Cappelli, Thin Solid Films **516,** 6668–6672 (2008).

[7] "High Speed Images of Drift Waves and Turbulence in Magnetized Microplasmas," T. Ito and M.A. Cappelli, IEEE Trans. Plasma Sci. 36, 1228 (2008).

(ii) Conference Publications or Presentations

[8] "Further Development of a Micro Hall Thruster," T. Ito, N. Gascon, W. Crawford and M. Cappelli, AIAA-2006-4495, 42nd Joint Propulsion Conference, Sacramento, CA, July 9-12 (2006).

[9] "Further Development of a Micro Hall Thruster," T. Ito, N. Gascon, W. S. Crawford, M. A. Cappelli, Proceedings of the 42nd Joint Propulsion Conference, Sacramento, CA, July 9-12, (2006).

[10] "Measurements in Stationary Reference Bi Discharge Cell for Diagnostics of a Bismuth Hall Thruster," D. B. Scharfe, T. Ito, M. A. Cappelli, Proceedings of the 42nd Joint Propulsion Conference, Sacramento, CA, July 9-12 (2006).

[11] "Development of a Magnetized Microdischarge Ion Source," T. Ito, M. A. Cappelli, The 24th Symposium on Plasma Processing, Osaka, Japan, January 29-31 (2007).

[12] "Experimental characterization of a Hall-effect microdischarge ion source," T. Ito and M.A. Cappelli, The First International Symposium on Atomic Technology, March 16-17, Tsukuba, Japan (2007).

[13] "Neutral Energy Distribution Impinging on the Cathode in Direct-Current Discharges," T. Ito, M. A. Cappelli, Spring Meeting 2007 of the Japan Society of Applied Physics, Kanagawa, Japan, March 27-30 (2007).

[14] "Energetic Neutral Particle Production in the Cathode Sheath of Direct-Current Discharges," T. Ito, M. A. Cappelli, Proc. 18th Int. Symposium on Plasma Chemistry (ISPC-18), Kyoto, Japan (2007).

[15] "Magnetized Microdischarges in Low Pressure Environments," T. Ito, M. A. Cappelli, 20th Symposium on Plasma Science for Materials (SPSM-20), Nagoya, Japan, June 21-22 (2007).

[16] "Neutral Energy Distribution in the Cathode Fall of Direct-Current Glow Discharges," T. Ito and M.A. Cappelli, 60th Gaseous Electronics Conference, Arlington, Virginia, USA, October 2-5 (2007).

[17] "DC and Pulsed Magnetized Microdischarge Plasma in Low Pressure Environments," K. Kobayashi, T. Ito, M. A. Cappelli, and S. Hamaguchi, The Second International Symposium on Atomic Technology, Book of Abstracts P-33, October 1-2, Awaji, Japan (2008).