

FINAL REPORT ON
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FA9550-07-1-0003:

**“MICROPLASMA CHANNELS AND LARGE ARRAYS:
APPLICATIONS TO PHOTOMEDICINE, MICROLASERS, AND REACTORS ON A CHIP”**

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I. SUMMARY OF ACCOMPLISHMENTS

Under the support of AFOSR grant no. FA9550-07-1-0003, our laboratory at the University of Illinois has pursued the science and applications of microcavity plasmas, both as single devices and in the form of large arrays. Because of its unique properties, microplasma technology has (we believe) profound implications for photonics and electronics, with applications ranging from general lighting to biomedical diagnostics. During the past 3 years, the following milestones have been reached under this AFOSR program:

1. The plasma bipolar junction phototransistor (PBJT) has been discovered. A hybrid plasma/semiconductor device in which a microplasma replaces the collector in an otherwise conventional *npn* transistor, the PBJT is capable of switching and modulating a plasma with a base-emitter voltage of $< 1\text{V}$.
2. Large arrays of microcavity plasma devices have been fabricated from a single sheet of aluminum foil by a sequence of wet chemical processes in which the electrodes and interconnects are formed automatically while simultaneously being encapsulated in alumina.
3. The ability to reproducibly fabricate microcavities of controllable cross-section in Al or Al_2O_3 has been demonstrated. Arrays of cavities having a parabolic cross-section and all dimensions specified to within $\pm 4\%$ can now be fabricated over an area of hundreds of cm^2 .
4. Ellipsoidal microcavities and parabolic cross-section microchannels have been fabricated in glass and crystals (such as CaF_2) by a nanopowder blasting technique developed in our laboratory.
5. Microplasma lamps of large area ($\geq 100\text{ cm}^2$) have been fabricated in Al wire fabric (screen) and characterized.
6. As a direct result of AFOSR funded research, a new company (Eden Park Illumination) was launched in 2007. Today, the company employs eight individuals full time.
7. Over the approximately $2\frac{1}{2}$ years in which this grant has been in force, six U. S. patents have been awarded (three more have recently been allowed), and 13 patent applications have been submitted to either the U.S. Patent and Trademark Office or to Patent Cooperation Treaty (PCT) headquarters in Europe.

These are only a few of the accomplishments realized to date under this AFOSR grant. Other highlights include the discovery of a new pumping technique for atomic lasers (utilizing a

transient molecular intermediate species), and the application of atomic wavepackets to the direct measurement of the nascent product distribution produced by a dissociating molecule.

The remainder of this report describes several of these accomplishments in more detail and lists the more tangible results of the grant (publications, patents, and students graduated). Before reviewing these accomplishments, let me first express my thanks to AFOSR and Dr. Howard R. Schlossberg, in particular, for the support of this research and development effort.

II. DESCRIPTION OF MAJOR ACCOMPLISHMENTS TO DATE UNDER AFOSR GRANT FA9550-07-1-0003

With AFOSR support, our laboratory at the University of Illinois has, for the past decade, investigated the characteristics of nonequilibrium, low temperature plasma generated within microcavities. This effort has led to an entirely new technology by which large arrays of microplasma devices can now be fabricated in inexpensive substrates such as glass, or even aluminum foil. Arrays having radiating areas of hundreds of cm^2 are now available and cavity cross-sectional geometries can be specified precisely by wet chemical processing. Owing to this technology developed solely with AFOSR support, a new company was launched during this past three year term (in April of 2007) for the purpose of manufacturing microplasma-based lamps for general lighting. The company currently employs eight individuals full time, is constructing flat lamps offering radiating areas of up to 400 cm^2 and a luminous efficacy $\sim 25 \text{ lumens/W}$, and recently received the Red Herring 100 Award.

This section is devoted to briefly describing several of the most significant results obtained under AFOSR grant No. FA9550-07-1-0003, including the demonstration of the first electronic device in which an electron-hole plasma is coupled to its gas phase counterpart.

A. Discovery of the Plasma Bipolar Junction Transistor

It has long been known that the electron-hole ($e^- - h^+$) plasma in a semiconductor bears a strong resemblance to a gas phase plasma. In particular, because the electron mobility in the gas phase is much higher than that for the ions, the gas phase plasma acts in a manner very similar to that of an n - type semiconductor. In fact, the transport relations (diffusion, drift, recombination) for gas phase and semiconductor plasmas are virtually identical. We have exploited this similarity to demonstrate the plasma bipolar junction transistor (PBJT) in which a microplasma replaces the collector in an otherwise conventional $n p n$ BJT.

Figure 1 is a schematic diagram of a PBJT in a simple external circuit. With this device, the collector is a plasma which provides not only optical emission but also voltage and current gain. In normal operation of the PBJT, the emitter-base junction is forward-biased so as to inject electrons into the p-type base. The collector-base junction is, however, reverse-biased such that electrons diffusing from the emitter-base junction are swept into the collector. Thus, the operation of the PBJT is essentially identical to that of a conventional *npn* BJT. There are, however, several important distinctives of the plasma BJT. Because most of the voltage imposed on a plasma appears across the sheath, the electric field strengths in the sheath of a microplasma, for example, are known to be on the order of hundreds of kV/cm. Since the sheath of the collector plasma in the PBJT extends to the surface of the base (i.e., base-collector junction), the intense sheath electric field penetrates into the 10 μm thick base a distance determined by the

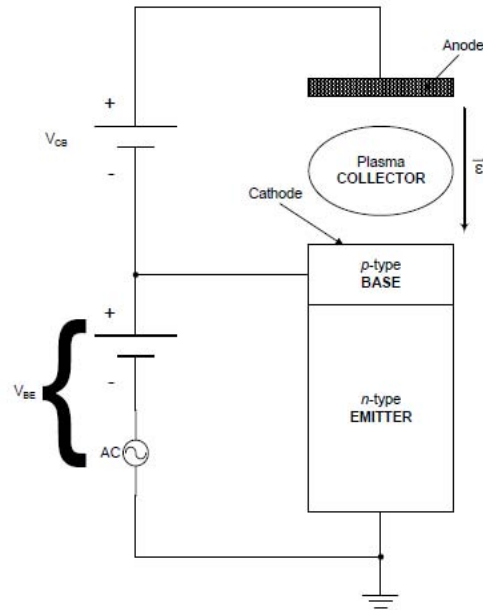


Fig. 1 Schematic diagram of an *nnp* plasma bipolar junction transistor in a simple external circuit. doping level of the base. Thus, the sheath electric field reinforces the built-in field normally present at the interface of a p-Si surface with vacuum.

As shown in Fig. 2, the sheath electric field steepens the slope of the potential barrier through which electrons from the base must tunnel in order to reach the collector. In other words, the tunneling of electrons into the collector is assisted by the intense electric field at the base- collector junction. A simplified diagram of the cross-section of one configuration of a PBJT is shown in Figure 3.

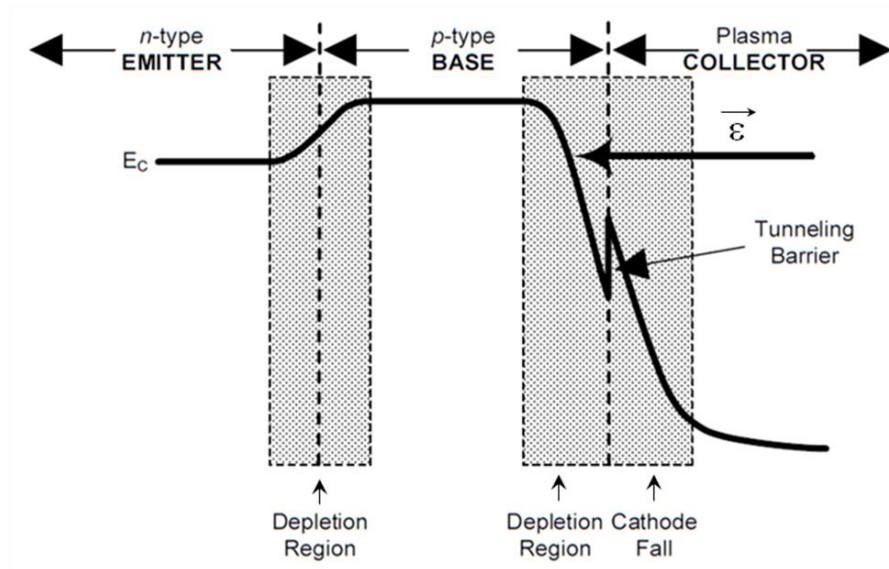


Fig. 2 Energy band diagram for an *npn* PBJT, showing only the variation of the conduction band edge energy E_c throughout the device.

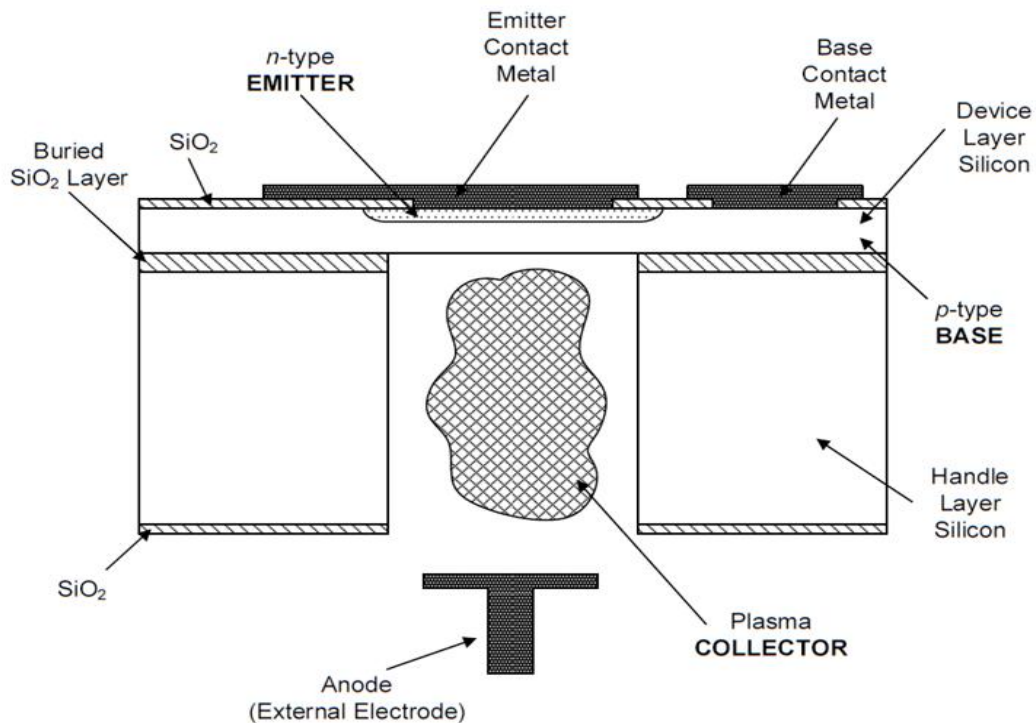


Fig. 3. Cross-sectional diagram of one configuration of an *npn* PBJT.

In this device, the plasma collector is produced in a 3 mm dia. cavity that is contiguous with a p-type base. The entire emitter/base structure has an overall thickness of only 15 μm and is

fabricated in Si. Figure 4 presents a set of 13 collector current (i_c) – base current (i_B) characteristics for the PBJT when the collector cavity has 25 Torr of Ne gas and V_{cc} is varied in 10 V increments from 270 V to 400 V. Note that i_c does not vanish when $i_B < 0$ because the device also operates as a phototransistor. That is, optical radiation from the collector plasma illuminates the base-collector junction, producing $e^- - h^+$ pairs and, therefore, generating a negative base current. The hysteresis evident in the $i_c - i_B$ characteristics of Fig. 4 is also unique to plasma transistors.

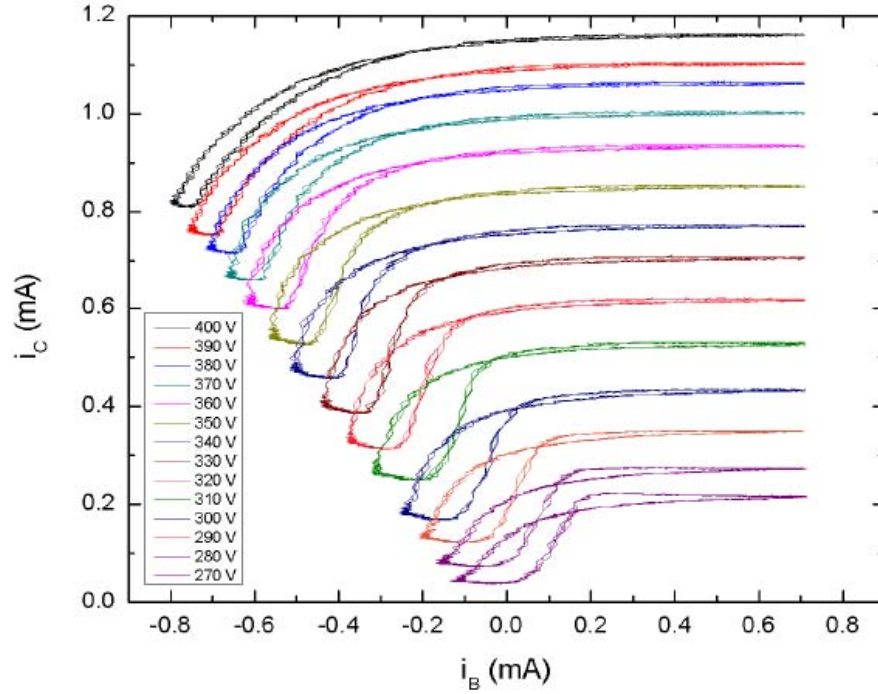


Fig. 4. $i_c - i_B$ characteristics for the *npn* PBJT of Fig. 3 when the collector pressure is 25 Torr (Ne).

With the PBJT design of Fig. 3, we have observed that collector plasmas can be fully extinguished with a negative voltage applied to the base and having a magnitude $< 1V$! This result has extraordinary implications for the future of plasma devices which normally require hundreds to thousands of volts for modulation purposes. We anticipate that the PBJT will have broad applications in displays and materials processing. Of greatest interest, however, is the new physics represented by this device.

Arrays of Microcavities with Self-Patterned Electrodes and Parabolic Geometry

The impetus to demonstrate and develop arrays of microplasmas occupying areas of hundreds of square centimeters arises from both fundamental science and applications. With regard to the latter, microplasma devices provide new functionality to fields as disparate as photonics and materials processing. Furthermore, virtually all applications envisioned at present require inexpensive processes for fabricating arrays of large active area, and the ability to precisely control the geometry of each cavity is a distinct asset. We have demonstrated the capability for electrochemically machining microcavities in nanostructured alumina (Al_2O_3) and, at the same time, automatically patterning electrodes. Starting from standard Al foil, this process is inexpensive, readily scalable in area, and has resulted in the reproducible fabrication of as many as 10^4 microcavity devices (with emitting apertures of $50\text{ }\mu\text{m}$) in an active area of 15 cm^2 . This processing sequence allows for the cavity cross-sectional profile to be varied continuously from a linear taper to parabolic while controlling all dimensions to within $\pm 4\%$.

Much of the process sequence for fabricating large arrays of microplasma devices is shown qualitatively in Fig. 5. Processing begins with Type 1140 or 1145 Al foil having a thickness between 30 and $70\text{ }\mu\text{m}$. An initial film of nanoporous aluminum oxide (AAO) is grown from the Al foil by an electrochemical process in 0.3M oxalic acid at 15°C . After encapsulating the Al_2O_3 – coated Al foil with photoresist, the desired microcavity array pattern is produced by conventional photolithography, and windows are opened in the photoresist. The AAO film within the windows is then removed by wet etching in a chromic acid solution, and cavities are subsequently micromachined in the underlying aluminum by an etching process in perchloric acid. The keys to specifying precisely the final profile of the microcavity sidewalls are the thickness of the initial AAO film and the time devoted to etching of the aluminum. The influence of the latter on the ultimate geometry of the microcavity is depicted in Fig. 6 which shows the sidewall profiles produced by etching Al for 60 – 120 min through a $50\text{-}\mu\text{m}$ square window in the AAO mask. Each of the profiles in Fig. 6 presumes an initial AAO film thickness of $\sim 2\text{ }\mu\text{m}$. Rigorous characterization of this process over a wide range of processing conditions reveals that the final cross-sectional profile of each microcavity can be described by the following relation: $y = At^{1/2}x^2 + Bt$, where A and B are constants, t is the time devoted to etching, and x and y are the horizontal and vertical coordinates (respectively) of Fig. 6. Of primary importance is the result that the cavity profile can be varied continuously from a truncated paraboloid to a linear taper by specifying the processing conditions.

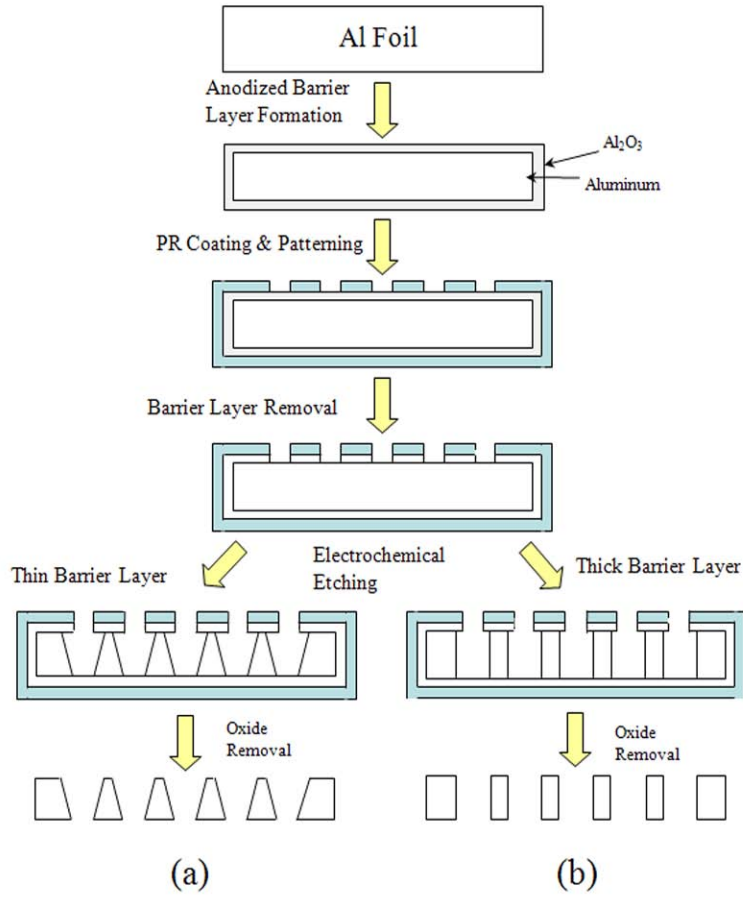


Fig. 5 Qualitative diagram (not to scale) illustrating the process flow for fabricating, in aluminum foil, microcavities having a predetermined and precisely controlled cross-sectional profile.

SEMs of representative microcavities produced in the thinnest foil investigated to date (30 μm in thickness) are presented in Fig. 7. Panel (a) of the figure is a plan view of a portion of an array comprising 10^4 cavities, each with an emitting (upper) aperture of 135 μm . The process sequence and Al foil thickness were chosen intentionally so as to have these parabolic cavities intersect both upper and lower surfaces of the foil, thereby yielding a lower aperture ~ 75 μm in diameter. Fig. 7 (b) is a magnified view of three microcavities, and panel (c) of the figure shows a cross-sectional view of four microcavities. It is clear from the micrographs of Fig. 7 that a “bowl-shaped” cavity (i.e., one having a parabolic sidewall profile) can now be fabricated reproducibly. Furthermore, systematic and extensive measurements of large arrays of microcavities show all dimensions of these wet chemical-fabricated cavities can be held to within a tolerance of several percent. From a microscopic examination of the cavities of the array of Fig. 7, for example, the diameter of the emitter apertures is 135.4 ± 4.9 μm , where the uncertainty (3.6%) represents one

standard deviation. Similarly, the lower aperture for the microcavities is $76.1 \pm 3.5 \mu\text{m}$. The emphasis on the fabrication of microcavities having precisely-specified parabolic sidewall profiles is motivated by the desire to optimize the extraction of light emitted within the microcavities, and to optimize the electric field distribution in the plasma.

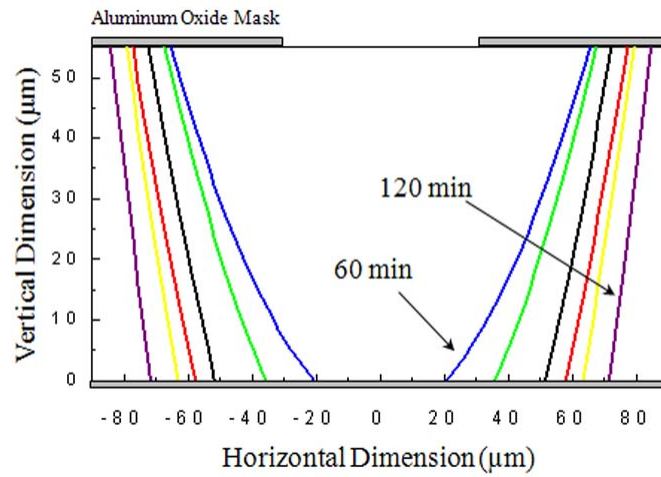


Fig. 6 Variation of the microcavity sidewall profile (from parabolic to a linear taper) with the etching time (Step 4) in process sequence (a) of Fig. 5. The curves shown represent the final microcavity cross-section for etching times of 60-120 min, illustrated in increments of 10 min. For clarity, the 110-min profile is not shown.

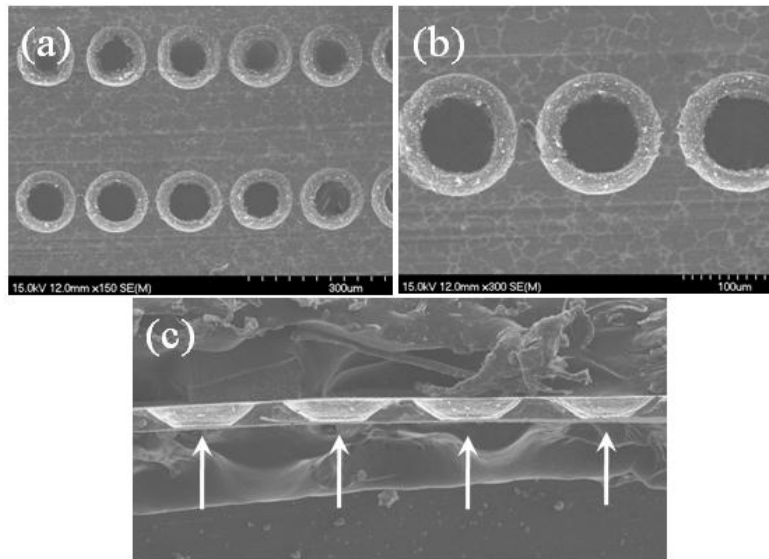


Fig. 7 SEMs of representative microcavities fabricated in 30- μm thick Al foil by processing sequence (a) of Fig. 5: (a) Plan view of a portion of an array of microcavities having an emitting (upper) aperture of 150 μm ; (b) magnified view of three microcavities, and (c) cross-sectional view of four microcavities (indicated by the white vertical arrows) having the “bowl-shaped” geometry.

In the same photolithographic step by which the locations of microcavities (i.e., the array pattern) are defined, one also specifies the ring electrodes encompassing each microcavity as well as the arrangement of Al strip interconnects. The processes by which the interconnects and electrodes are formed are not shown in Fig. 5. Nevertheless, the processing sequence yields Al interconnects and ring electrodes that are completely buried in nanoporous alumina. During the third and final anodization process (not shown in Fig. 5), the microcavity wall is transformed from Al to nanoporous Al_2O_3 , and the electrochemical conversion process accurately preserves the microcavity surface profile established by Al etching. An example of the arrays that can now be fabricated is given in Fig. 8 which presents optical micrographs of a portion of several linear arrays of 100- μm -diameter microcavities, interconnected by Al strips having a thickness of $\sim 15\ \mu\text{m}$ and a pitch of 125 μm . It must be emphasized that virtually all of the original Al foil has been converted into alumina, thereby yielding a finished structure (Al sealed in Al_2O_3) that is thermally and chemically robust and yet of low capacitance. As shown in Fig. 8, arrays of electronically interconnected microplasma devices can now be fabricated readily in Al foil with the individual microplasmas arranged in virtually any pattern.

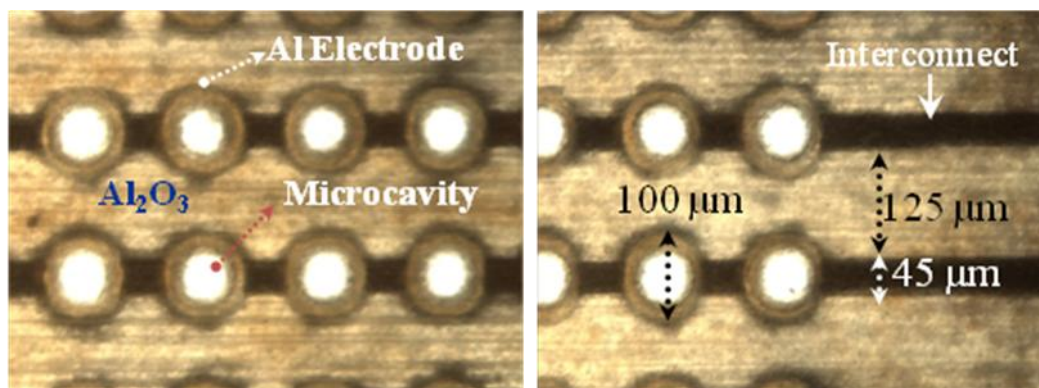


Fig. 8 Images obtained with a microscope and CCD camera of portions of linear arrays of Al_2O_3 microcavities having a sidewall profile that is parabolic. Also shown are Al strip interconnects (dark horizontal bars in the micrographs) having a width of 45 μm and a thickness of $\sim 15\ \mu\text{m}$. The interconnects transition to ring electrodes encompassing each microcavity.

The optical emission produced by these arrays is quite uniform as evidenced by the optical micrographs presented in Fig. 9. Both show portions of an array of 100 μm dia. microplasmas operating in 700 Torr of Ne. Sheets of these arrays are thin ($< 2\ \text{mm}$ when fully packaged), lightweight and the technology briefly described here appears to be readily scalable to areas beyond 2 m^2 .

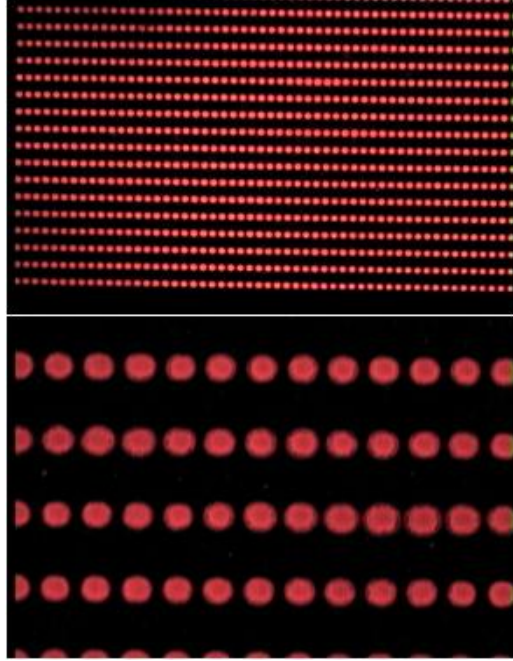


Fig. 9 (Top) Optical micrograph of a portion of an array of 100 μm diameter microcavity plasma devices operating in 700 Torr of Ne. The nonuniformity in emission that is evident at upper left of the image is the result of deviations of the array surface from flatness. (Bottom) Magnified view of a smaller portion of the array.

C. Ellipsoidal and Half-Ellipsoidal Microcavities in Glass: Inter-Plasma Coupling Phenomena

Over the past three years, we have developed a degree of expertise in fabricating microcavities of differing cross-sections in glass. Specifically, we have successfully fabricated arrays of ellipsoidal, or truncated ellipsoidal, cavities in thin (200 μm – 700 μm thick) glass sheets. Figure 10 is a cross-sectional diagram of a portion of an array of ellipsoidal microcavity plasma devices, fabricated in two sheets of glass with thicknesses of 400–700 μm . Having major and minor axis lengths in the 400–700 μm and 150–500 μm ranges, respectively, these cavities are produced reproducibly by a nanopowder blasting technique developed in our laboratory. Half-ellipsoids are produced in one face of each of the two glass sheets and the two glass substrates are subsequently bonded. Indium tin oxide film electrodes deposited onto the top and bottom of the structure enable the array to be transparent. The areal capacitance of arrays of these devices ranges from 50 $\text{pF}\cdot\text{cm}^{-2}$ to $\sim 140 \text{ pF}\cdot\text{cm}^{-2}$.

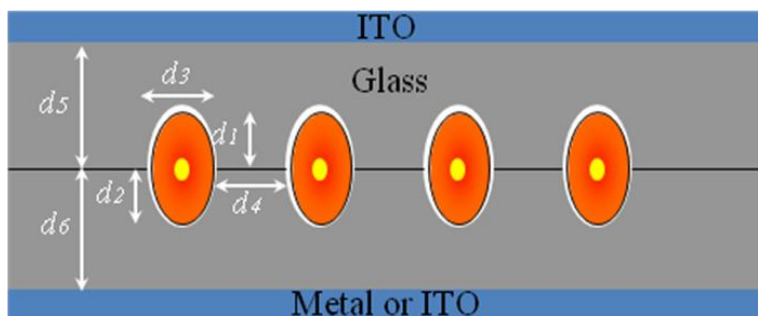


Fig. 10 Cross-sectional diagram of a portion of an array of ellipsoidal microcavities fabricated in glass.

Completely sealed arrays of ellipsoidal cavity devices have been fabricated and tested successfully, and Fig. 11 is a photograph of a 30 x 27 array of glass devices operating in 700 Torr of Ne. A magnified view of the array, recorded with a telescope and CCD camera, is presented in Fig. 12. It is clear that the most intense emission from the microplasma is localized at the center (midplane) of the device. Line outs of digital images of these microplasmas reveal that the emissive core has a diameter of $\sim 60\text{ }\mu\text{m}$, or $\sim 12\%$ of the midplane diameter of the ellipsoid. This value collapses to $\sim 30\text{ }\mu\text{m}$ when the cavity is a half-ellipsoid (i.e., a partial cavity is formed in only one of the two sheets of glass).

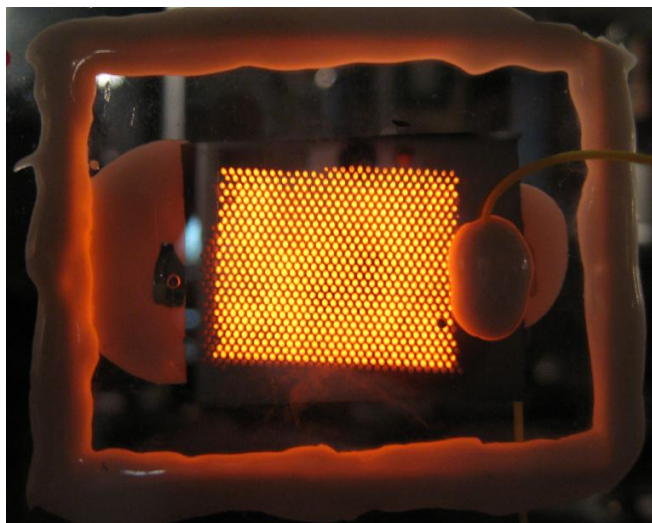


Fig. 11 Photograph of a small (30x27) array of ellipsoidal microplasmas operating in 700 Torr of Ne.

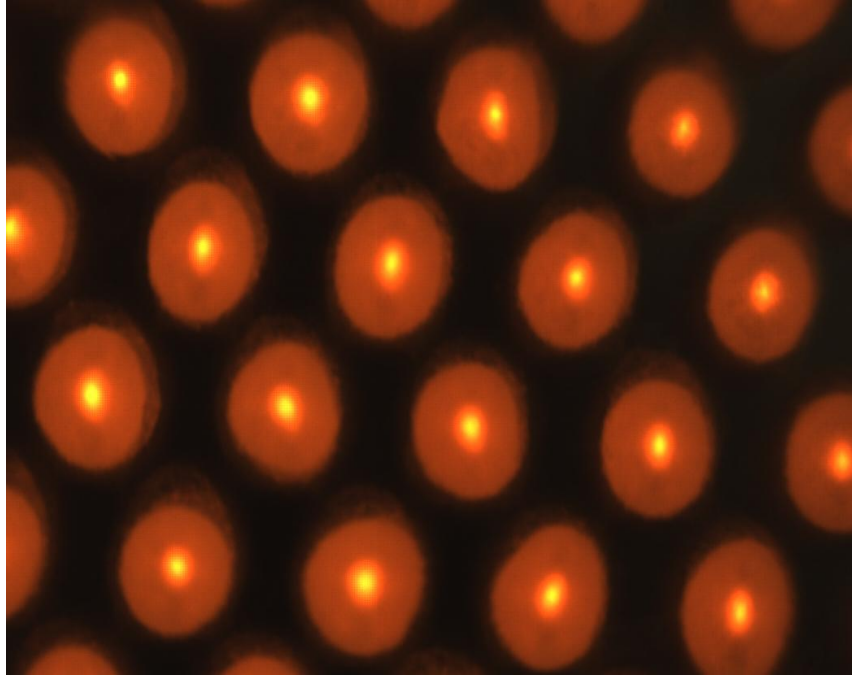


Fig. 12 Optical micrograph of a portion of an array of ellipsoidal devices. The Ne pressure is again 700 Torr and the 20 kHz driving voltage is 700 V (RMs).

Aside from the desire to produce ellipsoidal cavities for the purpose of tailoring the electrical field within the cavities, one goal of the design of the Fig. 10 structure is to investigate the possibility of coupling effects between microplasmas and its application to the control of collective phenomena. Figure 13 is a false color image of a portion of an array of ellipsoidal microplasmas, also operating in 700 Torr of Ne. Notice the clear extensions of each microplasma along the axes that connect the center of each microcavity with those of its nearest neighbors. These interactions do not appear to result from electrical coupling between microplasmas but rather from optical processes. One possibility is a variant of the optogalvanic effect in which atomic radiation (from Ne, in this case) is scattered by the ellipsoidal microcavity wall and is partially absorbed by neighboring microplasmas, thereby altering the local value of the electric field strength E . The primary motivation for this work continues to be the exploration of the characteristics of coupling effects in large arrays of microplasmas, and to apply electro-optical techniques to the control of collective phenomena.

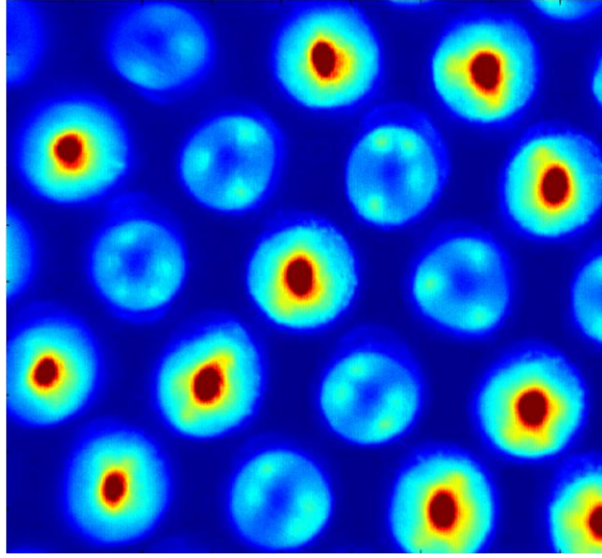


Fig. 13 False color image of a microplasma array having ellipsoidal cavities.

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V. GRADUATE STUDENTS AND POSTDOCTORAL RESEARCHERS SUPPORTED, DEGREES GRANTED

B. Ricconi – M.S. degree in Electrical and Computer Engineering, 2006
 Y. Xiao – Ph.D. degree in Electrical and Computer Engineering, 2007
 K.-F. Chen - Ph.D. degree in Electrical and Computer Engineering, 2008
 K. S. Kim - Ph.D. degree in Electrical and Computer Engineering, 2009
 Sung-Jin Park – Visiting Professor

VI. INTERACTIONS WITH INDUSTRY AND AF LABORATORIES

Collaborative interactions with industry and DOD laboratories have long been an important aspect of our work at Illinois, and such ties have strengthened over the past three years.

The continued expansion and development of the microplasma technology base, in particular, is drawing increased interest from both the government and companies. Under an Office of the Secretary of Defense (OSD) program administered by the Army, for example, we are a member of a team developing a microplasma-based infrared scene generator. This program recently passed a “go/no go” review that evaluated the spectral brightness in the mid-IR, switching speed, and pixel cross-talk of microcavity plasmas in Si devices. It is important to emphasize that all of the technology for this OSD program was originally demonstrated under the support of AFOSR and was first utilized for scene generator applications by Eglin AFB.

As part of another team, we are developing small microplasma arrays as microthrusters for nanosatellites. This is a new Air Force program but we have already demonstrated that Al/Al₂O₃ microcavities perform well as a microthruster, operating beautifully even at gas backing pressures >2.5 atm. Another small program recently underway is a collaboration with Lockheed Martin’s Skunk Works. Lockheed is interested in the applications of microplasmas as reconfigurable antennas. We have built several prototypes and tests of their RF and microwave characteristics are underway. Lastly, it should be mentioned that we continue to make our technology available (as best we are able) to colleagues of several universities around the globe. Many fellow scientists recognize the potential for these new plasma sources but they do not have access to the microfabrication facilities necessary to produce microplasma arrays. Although financial restraints limit our ability to accommodate requests, we are currently supplying a small number of arrays to colleagues at the University of Liverpool (UK), the University of South Australia (Melbourne), Bochum Universität (Germany), and Case Western Reserve University (Cleveland).