Arrays of Microplasma Devices Fabricated in Photodefinable Glass and Excited AC or DC by Interdigitated Electrodes

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***Abstract*—Arrays of microplasma devices, fabricated in a photodefinable glass and driven ac or dc by interdigitated electrodes outside the microcavities, have been fabricated and characterized. Operating in the abnormal glow mode for Ne pressures between 200 and 700 Torr and having characteristic cross-sectional dimensions of 75–100 μm, the devices are well behaved and arrays as large as 25 × 25 pixels have been tested to date. Focused on ease of assembly and minimizing cost, the design of these arrays makes them attractive for structures having emitting areas of hundreds of square centimeters.**

***Index Terms*—Arrays, glass, interdigitated, microplasma.**

FOUR DECADES ago, the first plasma display—monochrome and based on Ne—was demonstrated by Bitzer and Slottow [1], [2]. The advent of microcavity discharge devices, in which nonequilibrium plasmas are confined to cavities having cross-sectional dimensions as small as 10×10 μm^2[3], offers the potential for a new generation of high resolution displays but also provides functionality attractive for photonic applications in environmental sensing, biomedical diagnostics, and materials processing. Regardless of the application envisioned, scaling the radiating (active) area of microdischarge device arrays while minimizing cost and facilitating ease of assembly are primary considerations. Recently, arrays as large as $200 \times 200 (4 \cdot 10^4)$ pixels comprising $(50\ \mu\text{m})^2$ inverted pyramid microcavity discharge devices were successfully demonstrated in Si [4], but this materials platform is limited in scalable area by available wafer sizes and, thus, may not be optimal in those photonic systems for which maximum emitting area is essential.

This letter reports the design and operation of arrays of microplasma devices fabricated in a photodefinable glass in which each pixel has a circular or rectangular cross section and a characteristic dimension of 75–100 μm. Capable of being driven by either an ac or dc voltage applied to interdigitated electrodes on a substrate adjacent to the microcavities, arrays as large as 25 × 25 pixels have been tested to date and the structure described here appears to be scalable to radiating areas of hundreds of square centimeters (cm^2).

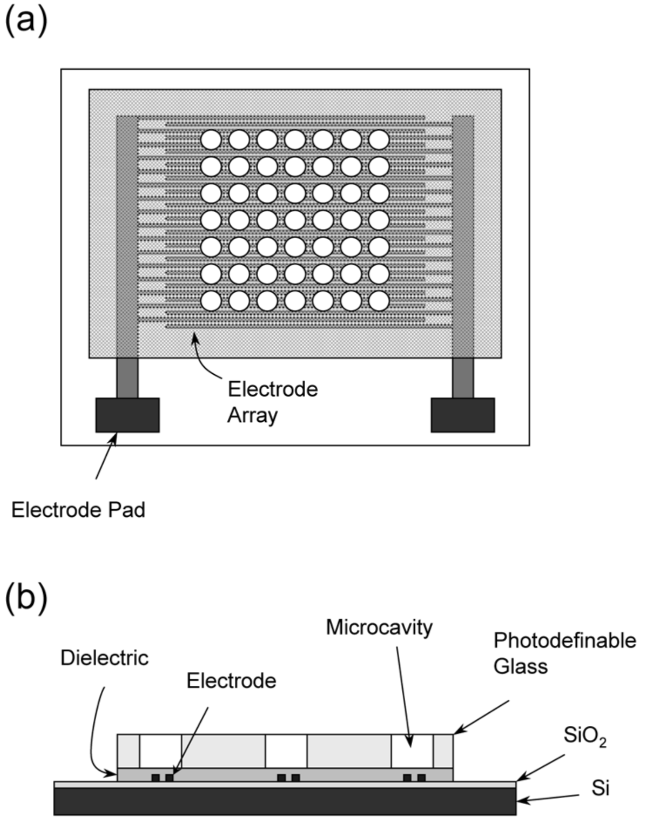

Fig. 1. (a) Plan view and (b) cross-sectional diagram of the microplasma device assembly. In the lower drawing, only a few of the equally spaced electrodes in the interdigitated array are shown. Neither diagram is to scale.

A cross-sectional diagram of a typical device structure is presented in the lower portion of Fig. 1. Microcavities having circular or rectangular cross sections are produced in a 0.5-mm-thick wafer of a commercially available photodefinable glass (Foturan) by standard photolithographic techniques and wet etching with hydrofluoric acid. The properties of this glass, including its dimensional stability, a refractive index of ~1.5 in the visible and a dielectric constant of 6.5 at 1 MHz, are well suited for large arrays of microplasma devices. Also, with careful attention given to processing conditions, the sidewalls of the microcavities are clean and the apertures of all pixels are uniform. Onto a p-type Si(100) wafer, which serves as the substrate for the electrodes driving the microcavity array, a 1-μm-thick film of thermal oxide is grown. Subsequently, an

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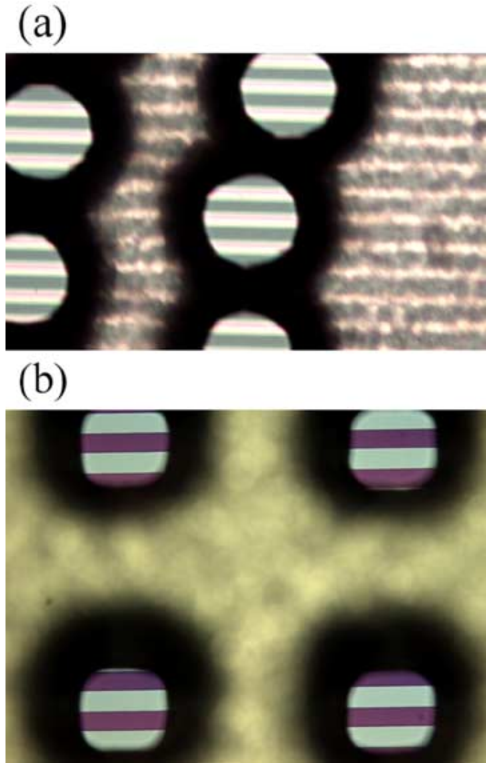

Fig. 2. Optical micrographs of (a) several 100-μm dia. microcavity discharge devices, and (b) nominally square ($\sim 100 \times 105$ μm^2) cross section cavities fabricated in Foturan glass. In both cases, the interdigitated electrode array can be seen on the far side of each microcavity, and the pitch and width of the electrodes are both 20 μm. These images were acquired with a telescope and CCD camera.

array of interdigitated Cr electrodes [cf. Fig. 1(a)], having a pitch (center-to-center electrode spacing) and an individual electrode width of 20 μm, is fabricated on the oxide by a liftoff technique. After overcoating the electrode array with a 2–10-μm-thick bilayer comprising a polyimide dielectric film and magnesium oxide, the Si and glass wafers can be sealed by one of several processes, including anodic bonding. For the experiments reported here, however, the arrays were not sealed but rather tested in a vacuum chamber in which the devices were evacuated to $\lesssim 10^{-6}$ Torr and back-filled with research grade Ne.

A key feature of this design is that the microcavity cross-sectional dimensions and the electrode pitch and width were chosen so as to facilitate the alignment of the electrode and microcavity array wafers, and ensure that each microcavity will have at least one pair of electrodes lying beneath it. Another asset of this structure is that, in the ac excitation configuration, the electrodes are not in physical contact with the plasma. Rather, the electric field produced by adjacent electrodes in the array extends into the microcavities, producing a plasma in a manner similar to that in a plasma display panel, for example. Isolating the electrodes from the microcavity has the inevitable result of raising the voltage required to ignite and sustain the microplasma but, as will be evident later, the penalty is not severe. As depicted in the lower portion of Fig. 1, the array requires ac excitation but in those situations in which dc operation is desired and the discharge medium is noncorrosive, one may dispense with both the dielectric and MgO protective layers. Most of the results reported here involved the full structure of Fig. 1 and driving the electrode array with a sinusoidal ac voltage waveform having a frequency of 20 kHz. Fig. 2 shows optical micrographs of two sets of microcavities. Both sets of pixels are segments of a larger array and Fig. 2(a) illustrates several 100-μm diameter (dia.) devices. The lower photograph in Fig. 2 is of four microcavities having a nominally square cross section of dimensions $\sim 100 \times 105$ μm^2. Both images were acquired with a telescope and charged coupled device (CCD) camera by viewing the pixels from above and, in each case, the underlying electrode array can be seen on the back side of the microcavities. The dark coloration around the perimeter of each microcavity is a refractive index artifact of the micrograph. Contrary to appearance, the glass wafer transparency is not altered by the microcavity fabrication process, even in the immediate vicinity of each microcavity.

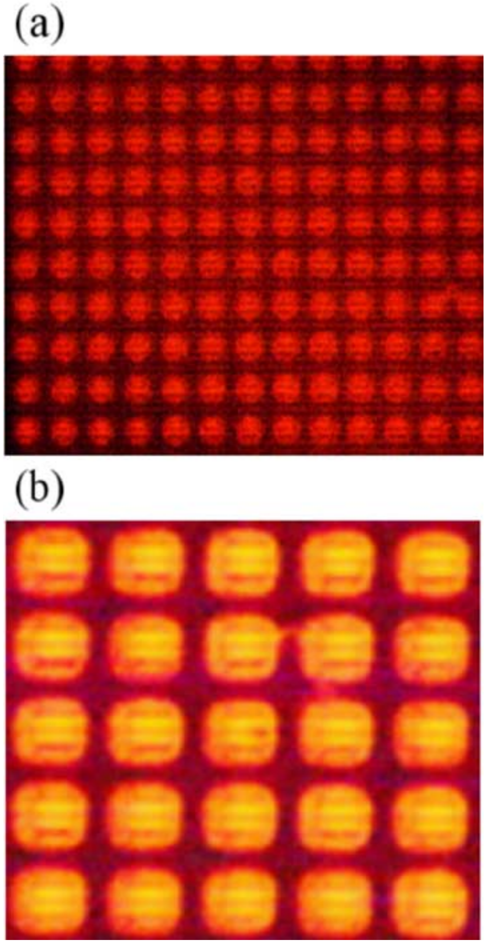

Fig. 3. Photographs of arrays of microdischarge devices having circular (top) or rectangular cross sections, and operating in Ne. The upper photograph shows a 13×10 segment of a 25×25 pixel array, excited ac (20 kHz) and the Ne pressure is 400 Torr. Each pixel has a microcavity diameter of 100 μm and the intensification of emission in the vicinity of the horizontally oriented electrodes is evident. A 5×5 array of ac-excited pixels having a (100-μm)^2 square cross section is shown in the lower portion of the figure. The excitation frequency is again 20 kHz, $V_{\mathrm{RMS}} = 196$ V, and $p_{\mathrm{Ne}} = 400$ Torr. Saturation of the CCD camera is responsible for the color rendering in this image.

Operation of the arrays with Ne at pressures between 200 and 700 Torr yields bright glow discharges in each pixel, as

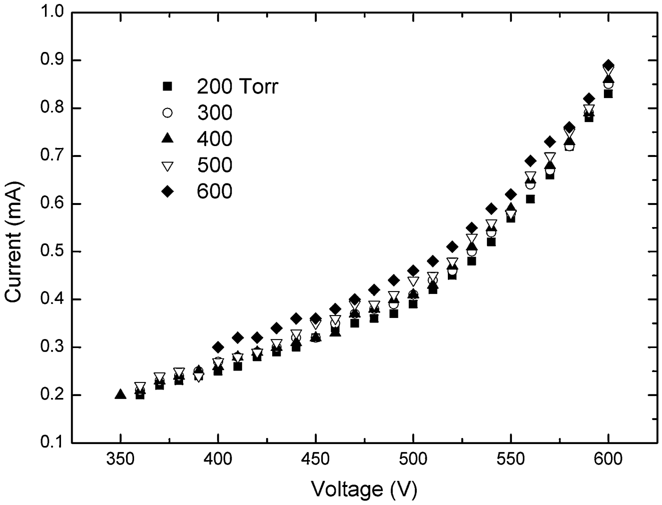

Fig. 4. Voltage–current (V–I) characteristics for a 5 × 5 array of $\sim 100 \times 100\ \mu\mathrm{m}^2$ rectangular cross section pixels and the Ne pressure varied between 200 and 600 Torr. The sinusoidal ac driving frequency is 20 kHz.

indicated by the photographs of arrays comprising circular or rectangular cross section microcavities shown in Fig. 3. In the upper panel, the microcavity diameter is 100 μm and the 25 × 25 array (of which only a 13 × 10 segment is shown) is operating in 400 Torr of Ne at a sinusoidal excitation frequency of 20 kHz and a driving voltage of 320 V root mean square (rms). Notice the intensification of emission within each pixel from the plasma region immediately above both electrodes. Similar comments could be made concerning the 5 × 5 array in the lower half of Fig. 3 for which the pixels have a rectangular cross section ($\sim 100 \times 100\ \mu\mathrm{m}^2$), $V_{\mathrm{RMS}} = 196$ V, and p_{Ne} is again 400 Torr. The differences in color rendering in the images of Fig. 3 are largely the result of saturation of the CCD camera in Fig. 3(b). With the present structure of the array, the emission intensity within each pixel, in the plane transverse to the axis of the microcavity, can vary significantly. Decreasing the electrode width and pitch, combined with a reduction in the thickness of the photodefinable glass wafer, is expected to improve considerably the intrapixel emission uniformity. Notice also that the effective aperture ratio (active, or emitting, area of the array normalized to its total area) for the array of Fig. 3(a) is only $\sim$20% but rises to $\gtrsim$50% with the square cross-sectional microcavities of Fig. 3(b). Our experience in fabricating these structures suggests that values in excess of 60% should be readily attainable.

AC voltage–current characteristics for a 5 × 5 array of $\sim$100 μm square cross section pixels are presented in Fig. 4 for Ne gas pressures ranging from 200 to 600 Torr, and an excitation frequency of 20 kHz. All of the measurements reflect rms values. As is generally the case for sub-150 μm microdischarge devices operating in Ne, the plasma resistance is positive over the entire current range investigated which is indicative of operation in the abnormal glow mode [3]. For a given value of operating voltage, the current rises with increasing pressure and, for array currents above $\sim$400 μA, the plasma resistance falls by more than a factor of three.

In summary, arrays of microplasma devices having a characteristic cross-sectional dimension of 75–100 μm have been fabricated in photodefinable glass and excited with interdigitated electrodes. When operating in Ne, the microplasmas exhibit abnormal glow behavior and $\sim$8 mW/pixel of dissipated power for a driving voltage and frequency of 500 V rms and 20 kHz, respectively. Designed for low weight and cost, these arrays appear to be scalable to radiating areas of hundreds of cm^2 and are of particular interest for therapeutic biomedical applications as well as low cost displays.

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