Microdischarge devices with 10 or 30 μm square silicon cathode cavities: \(pd\) scaling and production of the XeO excimer

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(Received 17 May 2004; accepted 22 September 2004)

Silicon microplasma devices with square trench cathode cavities having cross sections of (10 μm)\(^2\) or (30 μm)\(^2\) and a depth of 200 μm have been fabricated and operated successfully in the rare gases and Xe/O\(_2\) mixtures at pressures (300 K) up to 1100 Torr. The (10 μm)\(^2\) structures exhibit electrical characteristics that contrast with the behavior of larger devices and may indicate the onset of the breakdown of \(pd\) scaling. Also, a distinct minimum in the ignition voltage of 10 μm square devices is observed for \(pd=0.9\) Torr cm (\(p\) and \(d\) are the Ne gas pressure and microcavity cross-sectional dimension, respectively). Strong emission on the \(2^1\Sigma^+\rightarrow1^1\Sigma^+\) transition of XeO in the green (\(\sim510–560\) nm) is observed in mixtures of Xe (300–700 Torr) and O\(_2\) (1–10 mTorr). © 2004 American Institute of Physics.

Microcavity discharge device development is driven by the premise that confining weakly ionized plasmas to ever-decreasing dimensions will continue to yield optical devices for applications in biomedical diagnostics, photonics, and environmental sensing, but also provides access to a largely unexplored region of plasma parameter phase space. The former has been borne out by progress of the past few years and, specifically, the realization of single devices and arrays for emission,\(^1\) optical amplifiers,\(^2\) materials etching,\(^3\) and analytical spectrometry.\(^4\) Less is known, however, of the physics and behavior of devices having dimensions below 50 μm where surface interactions and the accommodation of the cathode fall region within the microcavity\(^5\) are expected to become increasingly influential.

This letter reports electrical and optical emission data for Si microdischarge devices having square trench cathodes with cross-sectional areas of (30 μm)\(^2\) and (10 μm)\(^2\). The latter exhibit voltage–current (V–I) characteristics that differ markedly from those of larger devices of the same design. A clear minimum in the ignition voltage of 10 μm square devices is observed in Ne gas for \(pd=0.9\) Torr cm, where \(p\) and \(d\) are the gas pressure and characteristic cross-sectional dimension of the microcathode, respectively. Continuous operation of these devices at rare gas pressures up to 1100 Torr favors the formation of transient molecules and bright emission on the \(2^1\Sigma^+\rightarrow1^1\Sigma^+\) transition of the XeO excimer in the green (510–560 nm) is produced in (30 μm)\(^2\) devices with Xe/O\(_2\) (1–10 mTorr) gas mixtures.

Several aspects of the fabrication of microdischarge devices having square cross-section microcathode cavities have been described previously.\(^1,6\) As illustrated qualitatively by the inset to Fig. 1, the devices characterized in these experiments comprise a \(p\)-type Si substrate, a two component dielectric (a 200-nm-thick film of SiO\(_2\) or Si\(_3\)N\(_4\), and 8 μm of a dry-etchable polyimide), and a \(\sim200\text{-nm-thick Ni anode film. The patterned anode film served as a mask during the selective removal of the polymer film with an oxygen plasma etcher. Subsequently, a microcavity, having a square cross section of (10 μm)\(^2\) or (30 μm)\(^2\) and a depth of \(\sim200\) μm (maximum aspect ratio of 20:1), was produced in the Si substrate by deep reactive-ion etching. All of the experiments reported here were conducted at ambient temperature with research grade Ne or Xe and, unless stated otherwise, 1 Ω of external ballast.

Voltage–current (V–I) data acquired for (10 μm)\(^2\) and (30 μm)\(^2\) square trench microcavity devices operating in Ne at (room temperature) pressures between 700 and 1100 Torr are presented in Figs. 1 and 2, respectively. Stable operation

![FIG. 1. Voltage–current (V–I) characteristics of (10 μm)\(^2\) silicon trench microcathode devices operating in Ne at pressures from 700 to 1100 Torr. The data were acquired with 1 Ω of ballast and the inset is a generalized schematic diagram of the device structure. For all the devices, the depth of the square trench was 200 μm. Experimental uncertainties, representative of all of the data, are indicated for several measurements. The curves drawn here (as well as those in Figs. 2 and 3) are intended as a guide for the eye.](image-url)
of these devices at higher pressures than those explored here is undoubtedly feasible but the upper limit in pressure for our experiments was dictated by the constraints of our vacuum and gas handling systems. Notice that the operating voltages of the two sets of devices in Figs. 1 and 2 are \( \sim 100–150 \) V higher than those for 50 \( \mu \)m microcavities, irrespective of whether the larger cavity is an inverted pyramid or a square trench.\(^5\) Also, all of the \( V-I \) characteristics have positive differential resistivities, one indicator of operation in the abnormal glow mode. It is evident that the currents drawn by the \((30 \, \mu\text{m})^2\) devices are approximately an order of magnitude larger than those for the smaller (10 \( \mu \)m) structures, which is roughly consistent with the relative cathode cross-sectional areas.

The data of Figs. 1 and 2 point to the onset of the breakdown of \( pd \) scaling. As discussed by Kushner\(^5\) for inverted pyramidal microcavity devices, \( pd \) scaling is dependent upon the accommodation of the cathode fall within the microcavity which, in turn, dictates that the thickness \( l \) of the cathode fall region be less than \( d \). If, therefore, \( d \) is reduced until it is comparable to \( l \), continuing to confine the discharge in the microcavity requires an increase in the operating voltage, thereby raising the ion number density \( n_i \) and decreasing the extent of the cathode fall region [since \( l \propto (V_c/n_i)^{1/2} \), where \( V_c \) is the cathode fall voltage].

It is apparent in Fig. 1 that the differential resistivity for the \((10 \, \mu\text{m})^2\) devices declines as \( p_{Ne} \) is reduced. Of interest is the double inflection in the 900 Torr data that marks the transition from the behavior at lower pressures to the higher resistivities characteristic of \( p_{Ne} \geq 1000 \) Torr. For \( p_{Ne} = 700 \) Torr (\( pd = 0.7 \) Torr cm), however, the steep rise in voltage for currents above \( \sim 2.5 \mu \text{A} \) signals the start of the glow-to-arc transition (and electrode damage) and thus demarcates the lower limit of the \( pd \) operating range for this device. In contrast, the \( V-I \) characteristics for the \((30 \, \mu\text{m})^2\) device are well behaved throughout the pressure range investigated and, aside from the range in operating voltage, are remarkably similar to the \( V-I \) profiles for \((50 \, \mu\text{m})^2\) devices.\(^6\) All of the profiles of Fig. 2 exhibit similar behavior, with an initial linear increase in operating voltage, followed by a sharp inflection leading to a more rapid rise in current (i.e., smaller plasma resistivity). Both above and below

"saturation," the characteristics of Fig. 2 have similar slopes and the inflection point moves progressively to smaller currents as the Ne pressure is increased. These data reinforce the conclusion that \( d = 10 \, \mu \text{m} \) is insufficient, for the lower Ne pressures of Fig. 1 (\( p_{Ne} \leq 900 \) Torr), to support the formation of a fully developed cathode fall region.\(^5\) The improved confinement of the discharge within the microcavity that accompanies increasing pressures results in electrical behavior in the \((10 \, \mu\text{m})^2\) devices that more closely resembles that for larger microcavity structures.

Measurements of the ignition voltage of 10, 30, and 100 \( \mu \)m square Si microcavity devices over the \( pd \) range of 0.7–7 Torr cm are summarized in Fig. 3. The reproducibility of all of the measurements, \( \leq \pm 1 \) V, is indicated for several points in the figure. For \( pd \) values less than 5 Torr cm, the ignition voltage rises to \( \sim 350 \) V, is approximately constant between 2 and 3 Torr cm, and then declines sharply below 2 Torr cm. A distinct minimum is observed at 0.9 Torr cm \((d = 10 \, \mu \text{m}, p_{Ne} = 900 \) Torr\) and the voltage rapidly rises at lower \( pd \) values.

One final observation should be mentioned. The lifetime of \((10 \, \mu\text{m})^2\) devices operating in Xe was found to consistently, and significantly, exceed that for Ne. Device lifetimes were also observed to be longer for Xe in \((30 \, \mu\text{m})^2\) structures but the effect was especially pronounced for the smaller devices. It is likely that the low ionization potential of Xe, in concert with its poor thermal conductivity, is responsible for this behavior by better confining the discharge in the microcavity and near the axis of the device. This result, as well as the operating pressures accessible with \( d = 10–30 \, \mu \text{m} \) devices, suggests the opportunity to pursue as visible or near-ultraviolet emitters those Xe-bearing excimer molecules that have received scant attention previously, or are excited inefficiently, in larger microdischarge (or macroplasma) devices.

One example is the xenon–oxide (XeO) molecule from which lasing was first observed in 1974 (Ref. 7). Emission spectra of Xe/10 mTorr O2 gas mixtures in a \((30 \, \mu\text{m})^2\) device are shown in Fig. 4 for the \( \sim 350–850 \) nm spectral interval, and Xe partial pressures of 300, 500, and 700 Torr. For each of the three Xe partial pressures investigated, fluorescence produced by the \( ^1\Sigma^+ \rightarrow ^1\Sigma^+ \) transition of the ex-
n 700 Torr, which is more than two orders of magnitude larger than that produced in the same device by the well-known 6 1S 1D + XeO transitions of atomic Xe in the near infrared. Since the XeO (2 1Σ+) excited state radiative lifetime is (96 ps Xe) −1 s (p Xe is again expressed in Torr—Ref. 7) or ~15 μs at 700 Torr, which is more than two orders of magnitude larger than the Xe 6p 1D 1S 2 1S lifetimes of 30 and ~38 ns (Ref. 8), respectively, it is clear from the spectra of Fig. 4 that the steady state XeO population in the microplasma exceeds that of the Xe 6p states by an estimated three orders of magnitude.

The inset to Fig. 4 presents an expanded view of the XeO fluorescence spectrum and identifies several of the most prominent bandheads. In accord with electron-beam experiments, maximum intensity is observed for the (ν′,ν″)=(0,5) and (0,6) bands. Because the 2 1Σ1+ state is shallow and the quasi-excimer transitions terminate preferentially on higher-lying vibrational levels of the lower electronic state (1 1Σ1+), the XeO bands are red-degraded and the emission lies to the blue side of the dipole-forbidden auroral transition (1S→1D) of atomic oxygen at 557.7 nm.

In summary, microcavity discharge devices, having 10 or 30 μm square trench Si microcavities, have been fabricated and characterized with either Ne or Xe/O2 gas mixtures. The electrical and optical measurements reported here explore a previously inaccessible region of microplasma parameter space—namely, pd<1 Torr cm for d=10 μm. A clear minimum in the ignition voltage for pd=0.9 Torr cm and the V−l characteristics of (10 μm)2 devices suggest that the small cross-sectional dimension of the device is unable to support a fully developed cathode fall region for p Ne<900 Torr. Nevertheless, the stable operation of square trench microcavity devices with cross-sectional dimensions ranging from a few tens of μm to below 10 μm makes a class of diatomic and polyatomic emitters (such as the triatomic rare gas-halides: RgX, where Rg and X are rare gas and halogen atoms, respectively) of renewed interest in microcavity discharge pixels generating near-ultraviolet and visible radiation.

Discussions with M. J. Kushner and the technical assistance of K. Collier are gratefully acknowledged. This work was supported by the U.S. Air Force Office of Scientific Research and the Electric Power Research Institute.