Organic light-emitting device on a scanning probe cantilever

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Organic light-emitting devices (OLEDs) were fabricated on scanning probe cantilevers using a combination of thermally evaporated molecular organic compounds and metallic electrodes. Ion beam milling was used to define the emissive region in the shape of a ring having a diameter of less than 5 μm and a narrow width. Stable light emission was observed from the device at forward bias, with a current-voltage response similar to that of archetypal OLEDs. Based on this device, a novel electrically pumped scanning optical microscopy tool is suggested. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2353816]

Microscale optical microscopy techniques such as scanning near-field optical microscopy[1] (SNOM) have proven to have great potential for the study of nanostructured semiconductor,[2] ferromagnetic,[3] photonic,[4,5] biological,[6] and single molecule[7] systems. SNOM is primarily an optically pumped technique, with the two most standard realizations being aperture-based and apertureless probe architectures. In aperture-based SNOM, light is coupled to a sample through a hollow pyramid[8–10] or through a pulled optical fiber with a partially etched metal cladding.[1] In apertureless SNOM probes, light typically floods a metallized probe tip, exciting surface plasmons at the tip, with the evanescent field coupling to a sample.

Several attempts have been made to demonstrate electrically pumped microscale light sources. Sasaki *et al.*[11] have demonstrated a microfabricated optical probe integrated with a light-emitting diode (LED), waveguide, and aperture; the LED, however, was not monolithically integrated but rather glued to the cantilever, making for a less robust design. More recently, Heisig *et al.*[12] demonstrated 80 nm imaging resolution using a GaAs vertical cavity surface emitting laser integrated with a GaAs cantilever. However, while the direct band gap III-V materials have favorable light emission properties, they cannot be grown easily with high optical quality on Si (the most common material used for fabricating scanning probes) due to lattice mismatch and the formation of antiphase domains.[13] Scanning probe cantilevers made from III-V materials are hard to fabricate and typically show low yield[14] compared to standard Si micromachining techniques which enable batch fabrication.

In contrast, light-emitting devices based on thin films of van der Waals-bonded molecular organic compounds can be deposited onto a variety of substrates without the lattice-matching constraints of conventional covalently bonded semiconductors.[15,16] The availability of a wide range of luminescent dyes provides an additional degree of freedom in tuning the spectral characteristics of the organic light-emitting device (OLED), which coupled with the above considerations make OLEDs a promising candidate for integra-

tion with the well-established atomic force microscopy scanning probe platform. In the present work, we introduce an electrically pumped microscale light source based on molecular OLEDs deposited directly onto conventional silicon scanning probe cantilevers (illustrated schematically in Fig. 1).

The fabrication of an OLED directly on a scanning probe cantilever requires the ability to define the electrical contact and emissive region much smaller than the width of the cantilever ($\sim$30 μm), and finer yet to enable high resolution imaging. The patterning of a nanoscale OLED on a scanning probe cantilever is complicated, however, by the incompatibility of the organic active layers with typical semiconductor processing and patterning techniques. Several nanoscale OLEDs on relatively large planar substrates have been recently reported. Suh and Lee[17] have shown sub-100-nm vacuum-deposited OLEDs on broad-area indium tin oxide (ITO) substrates with a spin-coated and prepatterned insulator layer. More recently, Yamamoto *et al.*[18] have spin coated a polymer emitter into small wells in silicon nitride on a planar conducting substrate, followed by deposition of a cathode. Boroumand *et al.*[19] used a combination of electron beam lithography and spin coating to make a 100 nm diameter device in a silicon dioxide well on ITO. However, surface tension effects and probe fragility render the spin-
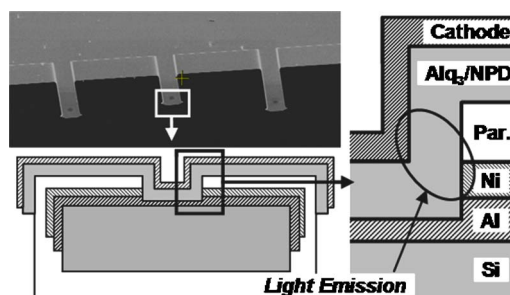

FIG. 1. Scanning electron micrograph of the scanning probe cantilevers, along with an illustration of the cross section of the organic light-emitting devices (OLEDs) fabricated on the cantilevers. The layer structure is Al (100 nm)/Ni (13 nm)/α-NPD (50 nm)/Alq$_3$ (60 nm)/LiF (0.5 nm)/Al (1 nm)/Ag (18 nm). The organic layers and cathode were deposited on the front side of the cantilever after milling the parylene insulator and anode by a Ga$^+$ ion beam.

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coating process not well suited for placing either e-beam resist or active organic layers onto a scanning probe cantilever. In this work, an electrically pumped light emitter was fabricated on a scanning probe cantilever using vapor- and vacuum-deposited materials, while the emissive region was defined through the use of focused ion beam (FIB) milling.

Figure 1 is a cross-sectional schematic of the emissive region of the scanning probe. A tipless Si cantilever was used, having a nominal width, length, and thickness of 35, 90, and 2 μm, respectively. The anode consisted of 100 nm thick aluminum, capped by 13 nm of nickel, thermally evaporated onto the cantilever, and followed by a conformal 800 nm thick electrically insulating layer of vapor-deposited parylene-C.[20,21] The active region on the cantilever was formed by milling the insulator with a focused gallium ion beam (FEI 3D Dual Beam FIB), with an accelerating field for the Ga$^+$ ion of 20 kV and an applied current of 0.76 nA. The material within the milled hole was characterized using energy dispersive x-ray detection, making it possible to mill in a controlled fashion through the parylene and only a portion of the anode.

Following the beam lithography step, the active organic layers were deposited by thermal evaporation at 10^{-7} Torr. The hole transporting layer consisted of 50 nm thick N,N'-di-[(1-naphthalenyl)-N,N'-diphenyl]-$(1,1'$-biphenyl)-$4,4'$-diamine (α-NPD), while the electron transporting and emissive layer consisted of 60 nm thick tris(8-hydroxyquinoline) aluminum (Alq$_3$). The cathode comprised a 0.5 nm thick layer of LiF, followed by a 1 nm thick layer of aluminum[22] and a 18 nm thick layer of silver. A control sample was prepared on a scanning probe cantilever having a layer structure identical to that on the probe, but without the FIB milling; the anode of the control sample was therefore separated from the active organic layers by a strong electrical insulator.

Electroluminescence (EL) from the OLED on the cantilever was detected through an upright microscope with a long working distance (20.5 mm) objective (50×, numerical aperture of 0.42) that facilitated making electrical connections to the device electrodes. To image light emission, a sensitive charge-coupled device (CCD) camera was utilized in a dark room. Figure 2(a) shows the CCD image of the OLED near the end of the tipless cantilever under external illumination. The dark ring indicates the walls of the milled region. Figure 2(b) shows the EL image of the OLED in Fig. 2(a) under forward bias. The EL emission is ring shaped even though the milled region is a disk, because holes at the anode are preferentially injected from the nickel due to it having a higher work function than aluminum. As shown in Fig. 1, the milling process removes the top nickel layer from the anode, leaving a ring-shaped region for hole injection from the nickel on the edge of the milled region into the active organic layers. The far-field light captured by the CCD is a combination of primarily the waveguided emission along the sides of the milled well and the scattering from the bottom of the well. The inset shows the EL intensity profile measured along the dashed line in Fig. 2(b). The full widths half maximum of each peak of the emission are 1.8 and 1.4 μm, respectively, as measured in the far field. Near-field enhancement of imaging resolution may occur at the top of the well, in proximity to the rim, due to the efficient coupling of energy from the electrically pumped dipoles to surface plasmon polariton modes that can propagate along the metal-
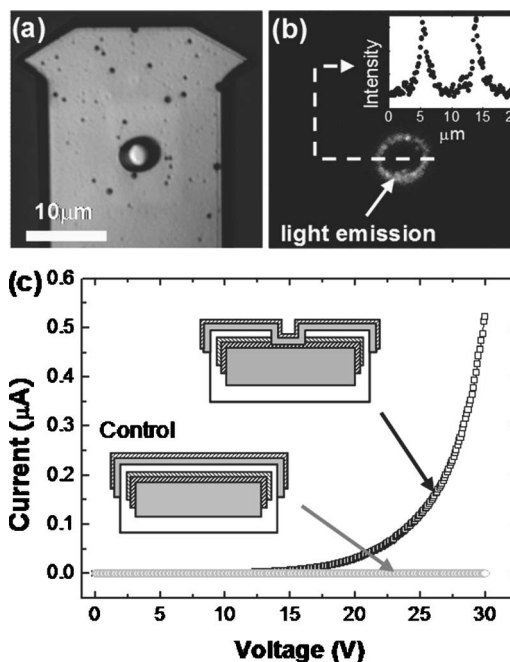

FIG. 2. (a) Micrograph of an unbiased OLED on a scanning probe cantilever under external illumination. (b) A micrograph image of an OLED on the cantilever under forward bias, showing electroluminescence (EL) in the shape of a 5 μm diameter ring. A CCD camera was used to capture light emission through a 50× objective lens with an exposure time of 200 ms. The inset shows the EL intensity along the dashed line which spans the ring-shaped emission. (c) Current-voltage (I-V) characteristics of the OLED scanning probe and control sample, indicating a very low leakage current in the OLED probe.

organic interface.[23,24] The near-field coupling of plasmon modes to a sample can occur at the rim of the well, in a manner analogous to that in apertureless SNOM.[25,26]

Each of three cantilevers (see Fig. 1) contained an OLED, and each OLED was of identical size and shared a common anode and a common cathode. All three devices were thus connected in parallel, and all emitted light simultaneously. Figure 2(c) compares the current-voltage (I-V) characteristics of the ring-shaped OLEDs on cantilevers with the control sample, both measured during optical testing using an Agilent 4156B semiconductor parameter analyzer. It is clear from the figure that the current passes through the OLED devices, and that the leakage current (i.e., the current through the control sample) is very small. The device emission and I-V characteristics shown here were similar for other sets of cantilever probes.

The device demonstrated here potentially can be used for a wide range of new probing techniques. The wavelength of emitted light can be tuned across the entire visible spectrum, including white light emission, by altering the composition of the emissive layer.[27] Should the ring-shaped light emission be used for imaging, the sample image can be deconvolved using a ring filter to achieve high resolution. The fabrication technique can be easily transferred to other cantilever substrates such as silicon nitride. The OLED probe can also be used to transfer excitons through the cathode to a sample via plasmon-assisted energy transfer;[25] such a probe would be valuable for studying exciton dynamics in organic or organic/inorganic hybrid photovoltaic devices.

In summary, 5 μm diameter and narrow width ring-shaped OLEDs were made on a scanning probe cantilever. Optical and electrical characteristics confirmed the operation

of the device with low leakage current. Such a device mounted on a cantilever could in the future be applied to techniques such as SNOM.

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