Electroluminescence Enhancement via Grating on a Si-based Plasmonic Metal-Insulator-Semiconductor Tunnel Junction

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Electroluminescence Enhancement via Grating on a Si-based Plasmonic Metal-Insulator-Semiconductor Tunnel Junction

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ABSTRACT

Here we fabricated and characterized a CMOS compatible metal-insulator-semiconductor (MIS) plasmonic tunnel junction for Si-based photonic circuitry. A grating structure was realized on MIS plasmonic tunnel junction via focused-ion-beam milling (FIB) to increase the intensity of the light emission that occurs during inelastic electron tunneling. Approximately 65 times higher intensity of light emission is achieved with the grating structure during the measurements.

INTRODUCTION

Conventional microprocessor interconnect performance cannot keep pace with semiconductor device scaling. To continue the pace of processor development which is critical towards this data-driven demand, interconnect technology must move beyond the inefficient charging and discharging of metal wires. The case for implementing optical interconnects has been made and the benefits are manifest [1]. The large bandwidth of optical waveguides can accommodate densely multiplexed signals. While an electrical line is limited to signaling at the clock frequency, an optical line can support channel capacities beyond terabits per second [2]. Optical signals provide speed-of-light signaling, mitigation of skew and voltage isolation problems, and near-ideal impedance matching at the photo-detector [1]. In addition to large performance gains, silicon photonics is a mature industry with detectors, modulators, waveguides and filters routinely fabricated with CMOS processing. The missing element in the realization of optical Si-based photonic circuitry is the silicon light source [3]. Development of that critical device with optimum performance, especially the intensity of light emission is the subject of this work. Different methods applied in previous works [4-5] to increase the light emission in MIS structures. However the maximum increase in the light emission in these previous works is not better than two times. Here we proposes grating structure to increase the intensity of light emission approximately 65 times.

THEORY

The schematic and mechanism of the proposed laser device to investigate is shown in figure 1. Note, the eigenmode of this structure is a photonic-plasmonic hybrid mode, which allows for high deep sub-diffraction limited optical modes [2], [6-8]. Electrically, the band diagram of this MIS junction is schematically shown in figure 1(b). The underlying physical processes are elastic and inelastic electron tunneling controlled by bias voltage. With each scattering event at the barrier, there exists a finite probability that the electron will tunnel into the conduction band to the semiconductor counter-electrode, conserving electron kinetic energy. After tunneling, the hot electron achieves thermal equilibrium, giving up its energy as heat.

Inelastic electron tunneling, in contrast, does not conserve electron energy. Instead, a photon is created as the electron transfers to a lower energy state in the metal counter-electrode (figure 1(b)). However, prior studies predicted the inelastic probability for a stimulated emission case to be up to 10% [9].

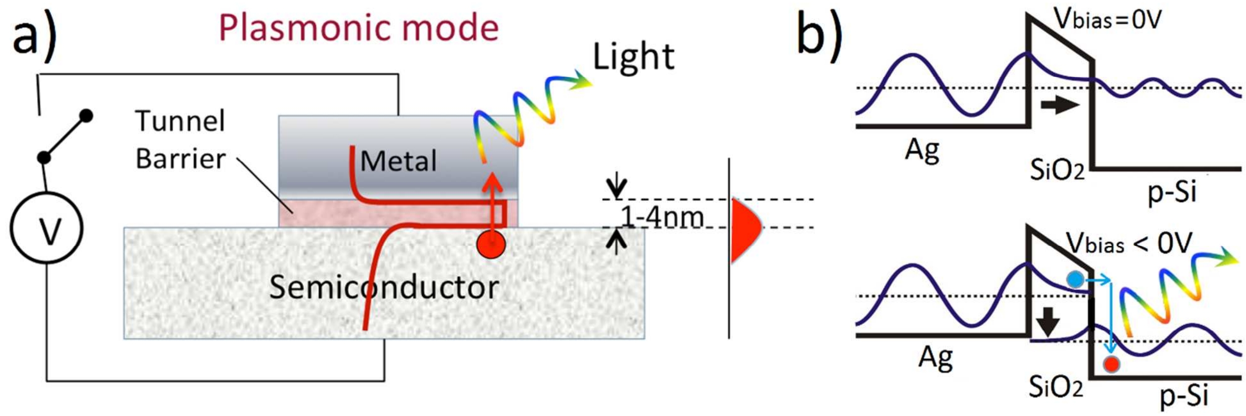

Figure 1. a) Schematic of the Silicon-based light emission process based on (i) tunneling electron (red) including their wave function, and (ii) a hybrid plasmon mode (HPP). b) Illustration of MIS junction operation, (top) elastic and (bottom) inelastic electron tunneling mechanism

The fabrication process started with a (100) p-Silicon wafer with a resistivity of 50Ωcm. A 300nm thick SiO2 was grown and etched all the way down to silicon wafer with a square mask. Next, approximately 2nm thick native oxide was grown and followed by 30nm Ag (top metal) and 100nm Au (pad) with 10nm Cr deposition to finalize the device in figure 2(a).

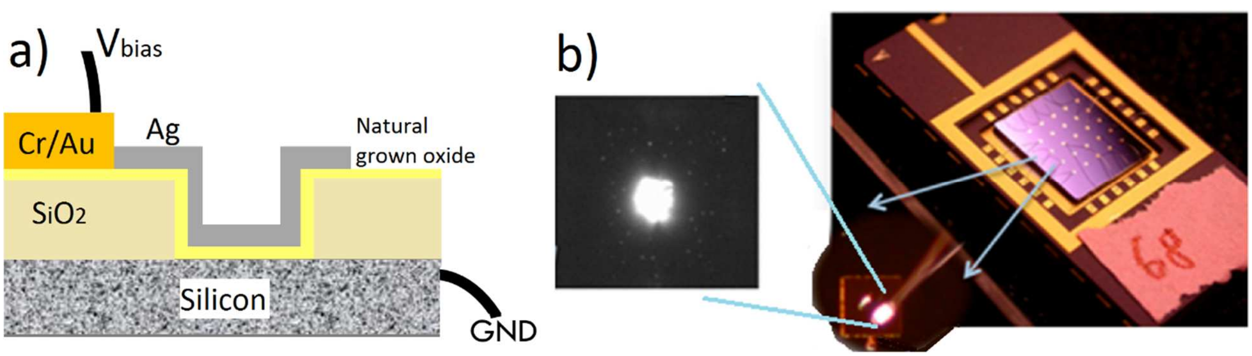

Figure 2. a) Schematic of MIS Junction, b) First devices on chip carrier are wire bonded for electrical contact with Electroluminescence (EL) spontaneous emission observed from the tunnel junction area.

The wafer with an array structure of MIS devices in figure 2(a) was wire bonded to CMOS chip after the post process, for the sake of characterization as shown in figure 2(b). The light emission was observed when the negative bias voltage was applied and results were recorded as demonstrated in figure 2(b).

DISCUSSION

After wire bonding on chip carrier in figure 2(b), the devices were tested to measure their EL intensity, however, a very weak light emission was observed as in Figure 3(a). A grating structure with a specific etch depth on top metal (Ag) was realized on the MIS structure as shown in figure 3(b) by using focused-ion-beam milling (FIB) in order to improve the out-coupling ratio. The EL intensity drastically increased with grating as seen in figure 3(b).

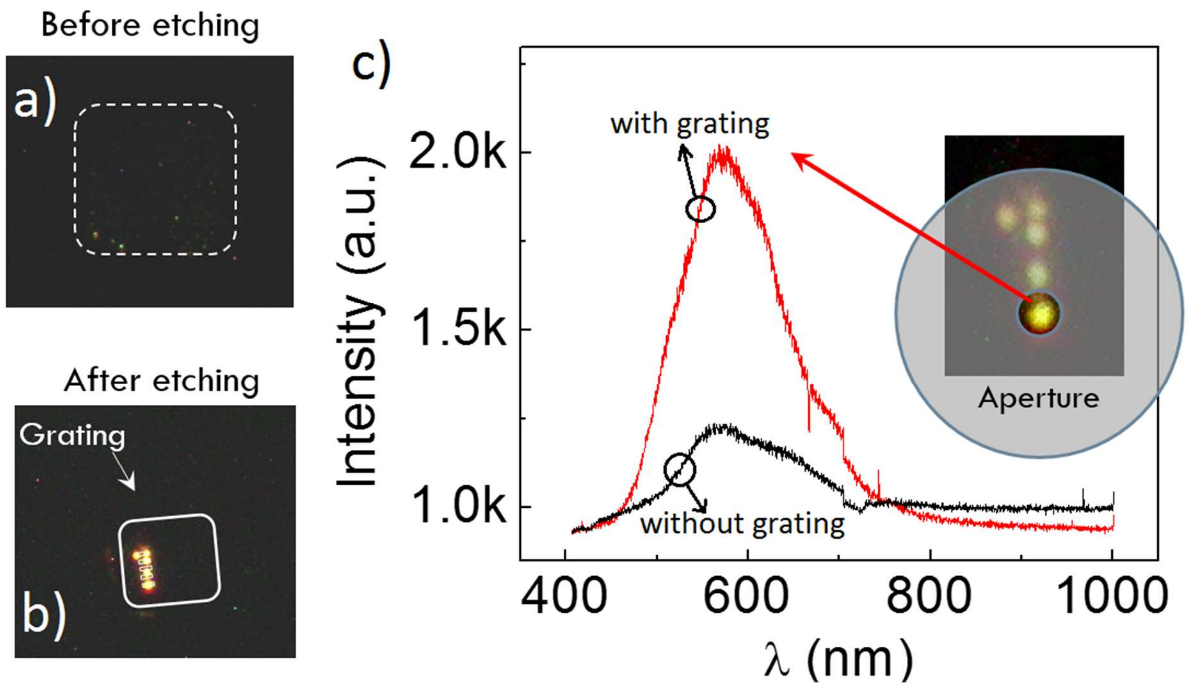

Figure 3. a) EL intensity of a biased MIS junction with an as-deposited metal film. Emission is weakly visible through the metal surface without grating. Device structure is guided by the dashed line. b) MIS EL after grating fabrication on the active device showing enhanced output (same voltage bias). c) Spectrum and EL intensity comparison showing out coupling enhancement of 65x of the grating over the metal pad. Measurement setup for MIS junction with grating has A~$1um^2$ (single spot) and t_{int} = 20s. Measurement setup for MIS junction without grating has A= $25um^2$and t_{int} = 30s, where, A is aperture opening area, and t_{int} is CCD integration time.

The light emissions for the MIS structure with and without grating were collected via free space objective (50x, NA=0.8), sent to the spectrometer and recorded via a liquid Nitrogen cooled CCD. It was observed that, the EL intensity increased roughly 65 times in figure 3(b) with the help of grating that enables accessing the sub-λ hybrid-plasmon-mode, and facilitating coupling into free space. The observed increased in EL could originate from the following reasons. The first one is the plasmonic mode that the sub-diffraction limited mode matching the optical mode with the length scale of the dipole moment of the tunnel electron. In addition, the grating structure provides the extraction enhancement. The last one is the edge effect. The edge of the metal grating could act as a resonant antenna, thus enhancing the electric field density of the optical mode. Detailed studies are needed to confirm the quantitative magnitude of each effect.

CONCLUSIONS

The metal-insulator-semiconductor (MIS) plasmonic tunnel junction for Si-based photonic circuitry was fabricated on p-Si wafer and grating structures were added on top metal (Ag) by focused-ion-beam milling (FIB). The light emission with negative bias voltage was observed during inelastic electron tunneling and results were recoded via spectrometer. According to measurement results, MIS with grating provides approximately around 65 times higher intensity of light emission in comparison with the MIS without grating. These results motivates for in depth study on grating structures on MIS junction for further enhancement in the light emission.

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