Light Emission from a Waveguide Integrated MOS Tunnel Junction

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Abstract: We report on light generation via inelastic electron tunneling in a metal-oxide-semiconductor (MOS) junction, which is directly integrated within a silicon photonic waveguide. We generate an optical power of 6.8 pW.

OCIS codes: (230.6080) Sources; (240.7040) Tunneling; (250.5403) Plasmonics.

1. Introduction

Light emitting tunnel junctions (LETJ) enable light generation without the need for a direct bandgap material by utilizing inelastic tunneling [1]. These light sources would be useful for on-chip applications such as sensing [2-4]. For this, light needs to be coupled to low-loss photonic waveguides (WG) to be distributed on the chip. The most commonly used tunnel junction for light generation consists of a plasmonic metal-oxide-metal (MIM) layer stack that is coupled to nano-antennas [2-6]. These structures promise internal quantum efficiencies of up to 10% due to a large local density of optical states (LDOS > 10^5) enabled by the plasmonic confinement [7]. Alternatively, LETJ are coupled to plasmonic WGs [8]. However, there have been no demonstrations to date of direct coupling of a LETJ to an integrated low-loss photonic circuit, as desired for on-chip applications. The main challenge is the large momentum ($\beta \approx 10k_0$) and short propagation length (100s of nm) of the excited light [9,10].

Here, we integrate an Au–SiO_2–Si LETJ to generate hybrid plasmons and directly couple them to photons guided in a low-loss photonic WG. We extract a coupling efficiency of ~75% and an absolute power of 6.8 pW that is emitted into the WG. The high coupling efficiency is attributed to the hybrid structure, which features no significant momentum mismatch as well as a propagation length of 4.3 µm rather than 100s of nm. Our experiments enabled us to estimate the internal quantum efficiency (photons/tunneled electrons) of a MOS structure to be > $4\text{x}10^{-6}$.

2. Operating principle

Fig. 1(a) displays an artistic view of the integrated tunnel junction on a silicon-on-insulator platform, with the inset illustrating the cross section through the tunnel junction (120 nm Au – 1 nm Ti – 3 nm SiO_2 – 340nm Si). A voltage applied across the junction shifts the Fermi level of the Au with respect to the Fermi level of Si and enables tunneling of electrons, as depicted in Fig. 1(b).

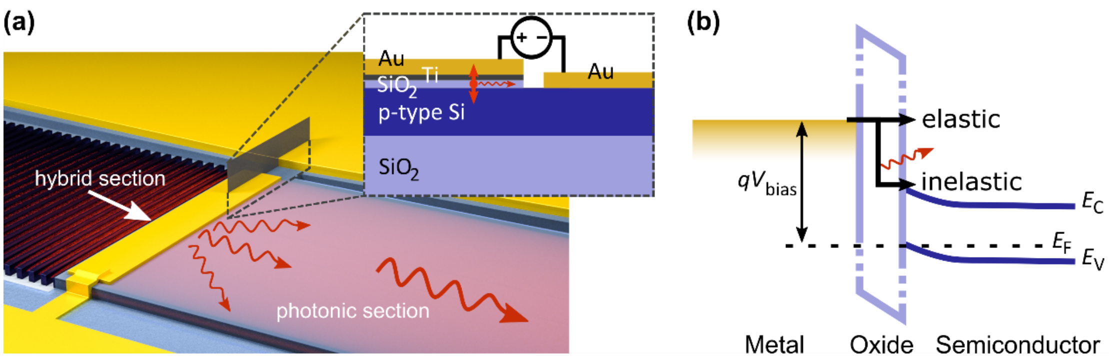

Fig. 1: (a) Rendering of a LETJ. Hybrid plasmonic modes are excited in the hybrid section and guided out in the photonic WG. The insert shows the cross-section (grey plane) through the structure. The emission is modeled as a dipole (red) perpendicular to the layer stack. (b) Band diagram of the MOS stack, showing possible elastic or inelastic tunneling pathways.

These electrons tunnel elastically or inelastically by exciting low-momentum hybrid plasmonic modes. The modes propagate towards the hybrid/photonic WG interface and couple to low-loss photonic modes. The generated light intensity that is coupled into the silicon WG is determined by the LDOS of the hybrid mode, the mode propagation length (L_P) and the coupling efficiencies ($\eta_{\text{hybrid}\rightarrow\text{photonic}}$). We calculate a LDOS of 250 ρ_0 for the hybrid structure, where ρ_0 is the LDOS of vacuum. This is ~20 times smaller than that of a MIM junction of similar oxide thickness. The hybrid mode L_P (4.3 µm) however is one order of magnitude longer than L_P of the MIM-mode. The coupling efficiency of the hybrid mode to the photonic WG is ~75%, a value that is difficult to achieve in MIM junctions coupled to photonic structures. This difference is due to the strong mode mismatch between the deeply sub-λ MIM mode and photonic mode.

3. Experimental results

We used standard SOI wafers with a 340 nm thick device layer and a 2 µm thick buried oxide as our platform. First, we patterned Si by dry-etching. Afterwards we patterned the Au contact pads to the p-doped ($1.35x10^{15}$ cm^{-3}) silicon. Next, we stripped the silicon's native oxide and deposited a 2.7 nm thick SiO_2 tunnel barrier via atomic layer deposition. Finally, an Au lift-off step was used to form the metallic top electrode of the tunneling junction using Ti as an adhesion layer.
Fig. 2(a) shows the device under test in the experimental setup. Light is generated by electrically pumping the tunnel junction with a Pico probe and extracting the photons with a multimode fiber (NA = 0.5, d_{core} = 200 µm) via edge coupling. First, we tested the quality of our tunneling junction by means of IV-measurements, see Fig. 2(b). Despite hour-long operation, the junction did not break as is evident by the characteristic feature between -1.3 V and 0.1 V of the blue tunneling curve. Only noise is measured due to the bandgap of the p-doped silicon. Intentionally broken junctions (red) no longer show this characteristic and current increases above the noise level. Fig. 2(c) shows the expected linear correlation between the measured optical power and the tunneling current. We measure a power of 1 pW coupled to the fiber, whereas the power flowing in the WG is estimated to be 6.8 pW when considering the NA of the fiber and interface reflections. We estimate an internal quantum efficiency (plasmons/tunneled electrons) of > $4x10^{-6}$ when taking into account the propagation losses and limited collection angles. Please note the limited bandwidth of the InGaAs photodetector and absorption in Si leads to an underestimation of this efficiency.

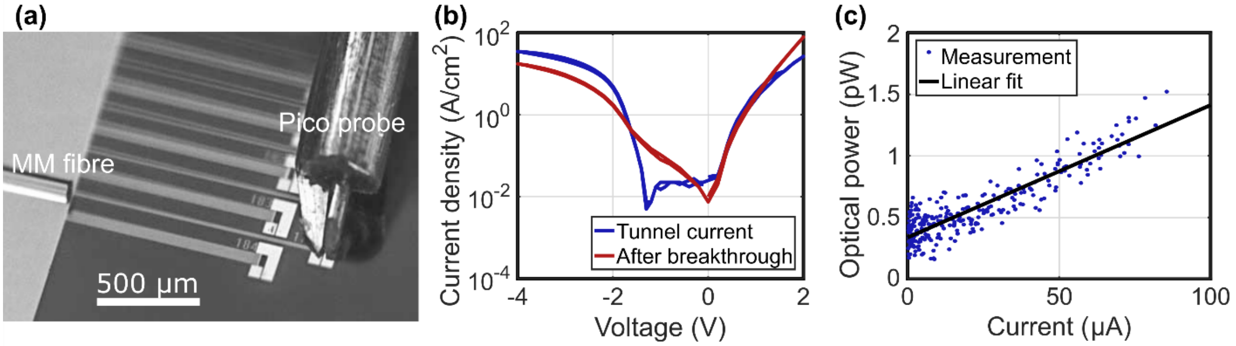

Fig. 2: (a) Photograph of LETJs. The Pico probe is used for electrical contact while the multimode (MM) fiber is used to extract the photons from the WGs. (b) IV curves of a broken (red) and unbroken (blue) tunneling junction. (c) Received optical power in the InGaAs photodiode versus the measured tunneling current.

4. Conclusion and Discussion

MOS tunneling junctions might pave the way towards a low-cost on-chip light sources as they can be monolithically integrated on a SOI platform. In comparison to MIM tunneling junctions, MOS junctions benefit from longer propagation lengths and a significantly improved coupling efficiency to compensate for the lower density of states. Additionally, the tunneling junctions have proven to be stable during hour-long operation, and thus might be a promising platform to study light generation by inelastic tunneling. This demonstration is a first prototype and there is ample room for optimization. For instance, avoiding the Ti adhesion layer already promises a 4-fold improvement.

Acknowledgments

This work was carried out at the BRNC of ETH Zurich. The EU-project ERC PLASILOR (670478) is acknowledged for financial support.

4. References

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