Integrated Photonics Driven Electron Emission from LaB_6 Nanoparticles

Fatemeh Rezaeifar, Rehan Kapadia
Department of Electrical Engineering
University of Southern California
Los Angeles, CA, USA, 90089

Abstract: *In this report, we demonstrate the novel approach of Integrated photonics driven electron emission from Lanthanum hexaboride (LaB_6) nanoparticles drop-casted over an optical waveguide. We use integrated photonic waveguide under electron emitter layer as a mean to transport the photons and evanescently couple them to emitter. This evanescent coupling occurs through longer interaction length and photons can be absorbed efficiently compared to free space laser illumination from top on a metallic emitter. Furthermore, nanoparticles with the average diameter of 4 nm are at the order of electron mean free path and electron emission occurs with fewer scattering compared to electron emission from bulky metallic emitters. As such, the higher optical absorption along with fewer scattering enable us with larger quantum efficiency electron emitters.*

Keywords: Integrated photonics; evanescent coupling; enhanced absorption; Optical V-groove; Si_3N_4 waveguide; LaB_6 emitter; electron emission.

Introduction

Photon driven electron emission is necessary for application such as free electron laser source, vacuum electronic high-power THz generation and ultrafast time-resolved electron microscopy. The existing photon driven electron beam are based on electron emission induced by focusing an intensified femtosecond laser pulse directly onto a surface of the metallic emitter. Unfortunately, this approach suffers from large reflection caused by metallic surface of the emitter. Metallic photocathodes have a work function higher than 4 eV and requires either a high energy photon or multiphoton contribution for electron emission. Small optical absorption of metallic photocathode results in power inefficient devices. Furthermore, photoexcited electrons inside bulk material suffer from multiple scattering that reduces their energy before emission to vacuum. As such the quantum efficiency of the existing photon driven electron emission devices are small. Researchers have investigated utilizing semiconductor materials for photon driven electron emission because of their larger optical absorption compared to metallic materials, however the emission process from semiconductors are highly unpredictable and exhibit a large energy spread. In addition, the 2D materials such as graphene have been considered for photon driven electron emission after their significant performance enhancement in field electron emission. However, the free space optical absorption of the monolayer graphene is limited to 2.3%.

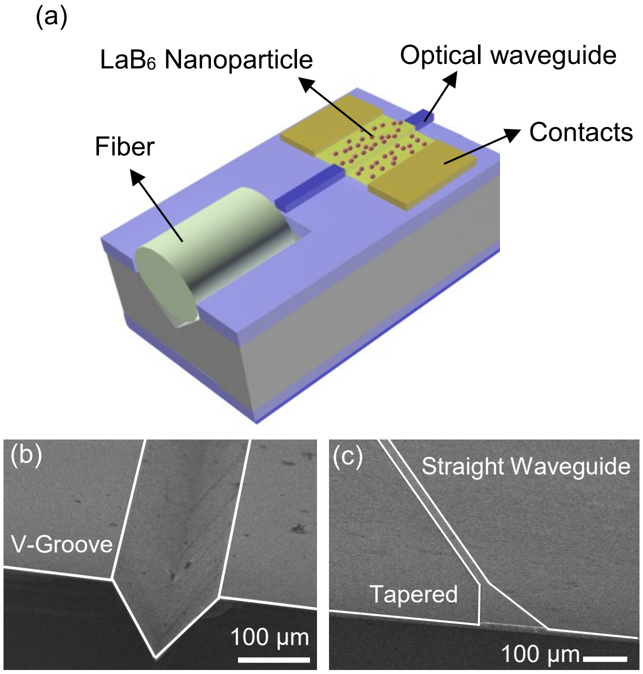

Figure 1. (a) Schematic of the integrated waveguide driven LaB_6 nanoparticle emitter on Si_3N_4 waveguide, (b) SEM images of fabricated V-groove, (c) Fabricated straight and tapered waveguide at coupling region.

In recent years, there has been remarkable developments on integrated photonics devices and on-chip laser via III-V material that can revolutionize photon driven phenomenon. In the present work, authors introduce utilizing an integrated photonics waveguide as a means of transporting photons to electron emitter instead of direct illuminations. In this approach, emitter will be placed over optical waveguide and photons will evanescently be coupled in to the emitter. We experimentally studied the photon driven electron emission characteristics obtained by evanescent coupling of CW laser (wavelength = 405 nm) to LaB_6 nanoparticle emitters drop-casted on Si_3N_4 integrated waveguide. We have selected emitter to be LaB_6 nanoparticles that have a diameter of 4 nm which is close to electron mean free path and as such electrons go through fewer scattering process. In addition, the work function of the LaB_6 is only 2.69 eV and it requires very small field to collect the photon driven emitted electrons. However, the integrated photonic driven approach is not limited to nanoparticles. 2D materials for example a monolayer of graphene on the surface of optical waveguide also works for this approach as an electron emitter.

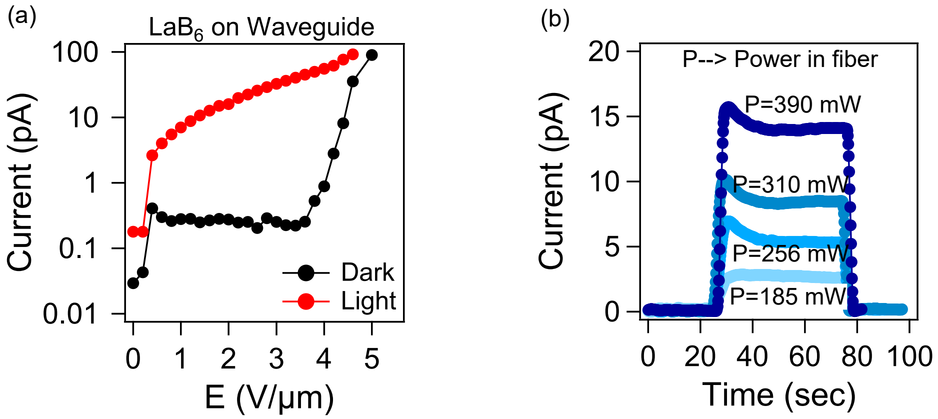

Figure 2. (a) Dark and light current detected from LaB$_6$ nanoparticles on integrated waveguide. (b) photocurrent dependency of integrated photonics driven emitter to laser power inside optical fiber at moderate E-field = 1.7 V/μm.

Device Fabrication

Schematics of the integrated photonics waveguide driven electron emitter is shown in figure 1a. We used lightly doped (1-10 Ω.cm) p-type silicon wafer (100) and fabricated V-groove using KOH anisotropic etching. Then, Si$_3$N$_4$ deposited via PECVD and waveguide formed after alignment with V-groove, patterning and RIE deep etching. The Si$_3$N$_4$ waveguide has a height of 5 μm and width of 50 μm. The SEM images of V-groove and waveguide are shown in figure 1b-1c. In the next step, two thick layers of Ti-Au (5nm - 100nm) electrical contacts evaporated at two sides of the waveguide. After contact fabrication, we deposited thin layers of Au (10nm) on the waveguide that is extended to two main electrical contacts. This layer assured a uniform contact for isolated LaB$_6$ nanoparticles. Then, we drop-casted LaB$_6$ nanoparticles on the waveguide. Finally, the optical fiber aligned properly inside V-groove with the opening of the tapered waveguide for optical coupling. We used customized fiber that has metallic shield made for propagation of high power 405 nm laser. This fiber has a diameter of 200 μm and we fixed the fiber inside V-groove using epoxy. Then, this sample loaded inside low vacuum chamber (5e-8Torr) for characterizing the photon driven electron emission.

Measurement Results

We used tunable CW laser source at wavelength of 405 nm and photocurrent detection was carried out using a Keysight B2985A electrometer connected via triaxial cable directly to our cathode. Figure 2a compares the I-E curves of the light emission with dark emission current prior to field emission. For light measurement, we used 390 mW of laser power at fiber end to couple the 405 nm laser in to waveguide. This prototype sample uses the cleaved fiber with diameter of 200 μm inside V-groove and due to size mismatch between the fiber and waveguide we can couple a few 100μW to waveguide that is the power level being absorbed by the LaB$_6$ nanoparticles on the surface of the waveguide. Under this condition, integrated photon driven emitter emits above 50 pA while dark current at the same E-field is below 1 pA. Furthermore, we noticed photocurrent detection starts at very small E-field, 0.3 V/μm whereas the dark field emission current detection starts at higher E-field, 3.5 V/ μm in which electron tunneling occurs. We also characterized the dependency of the light current to laser power (figure 2b) and observed the linear relation between the photocurrent and laser power at small E-field in which no tunneling is possible. This indicates single photon ability for this emission process and matches with the expected slope of 1 for single-photon absorption process, given the work function of the LaB$_6$ is only 2.69eV and our photon energy at 405 nm is 3.1eV. To compare the performance of the integrated photonics driven emitter with conventional free space coupled emitter, we measured the light current from directly illuminated LaB$_6$ nanoparticle with no waveguide. We could measure below 1 pA of photocurrent with 390 mW of laser input power from fiber. This experiment verifies the significant role of the integrated waveguide for increasing the optical absorption. As a result, larger photon driven emission current was measured from integrated photonics driven emitter compared to conventional free space illumination method.

Conclusion

In conclusion, we introduced a novel approach for photon driven emitters to increase their optical absorption and hence obtain an efficient electron emission. We studied the emission characteristics under different laser power and E-field for free space as well as integrated devices and compared the results. Authors refer reader to our paper for more details on theoretical calculation of this approach [1].

Acknowledgements

This work was supported by AFOSR Grant and USC Fund.

References

1. Fatemeh Rezaeifar, Rehan Kapadia, JVST B, Vol 34, Issue 4, July 2016.