Fabrication and optical characterization of erbium-doped silicon diode for quantum communication applications

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Abstract. Quantum Key Distribution allows two users to exchange secret keys and it is based on the transmission of single photons or attenuated laser pulses. Recently, sources based on multiple single-photon emitters were demonstrated to be suitable for QKD. Here, we present a CMOS compatible multiple single-photon emitters source realized on a SOI wafer by a standard silicon diode doped with erbium ions. Particular emphasis is placed on the fabrication of such a device enhancing the erbium electroluminescence signal by adopting a proper oxygen co-doping. Finally, electroluminescence characterization at room temperature of the device is presented.

1 Introduction

Quantum communication is expected to cover several market needs in the years to come [1]. For this reason, quantum key distribution (QKD) protocols have been implemented using both single photon sources and attenuated laser pulses, towards integration on photonic chips [2]. Recent works on the security bounds for decoy-state QKD have opened new opportunities for using sources with an arbitrary photon emission statistic, including weak sources based on multiple emitters [3].

In this work, we present the fabrication and a first optical characterization of a silicon diode doped with erbium that behaves like such a weak photon source, compatible with the emission of light at telecom wavelength at 1550 nm directly in a silicon chip [4].

The device consists of a silicon planar junction with a central region, nearby the p-n depletion area, doped with erbium and oxygen atoms. Upon setting a potential difference between the p-n regions, photons are created by the electroluminescence of erbium ions (Fig. 1). The expected advantages of this kind of device are its emission centered in the third telecommunication window (1520 nm - 1550 nm), its working range of temperature between 77 K and 300 K as well as a photon emission rate below 10 μs. To increase the number of optically active Er sites, an oxygen co-doping has been introduced [5].

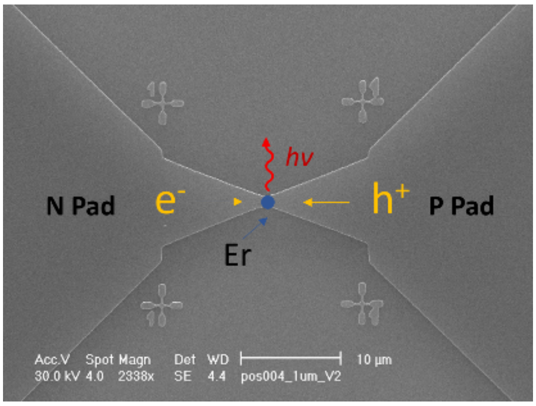

Figure 1. A scanning electron microscope image of one of the fabricated devices. In this device the erbium-doped central area is 1 μm × 1 μm. Since there is no waveguide, photons are emitted in free space.

2 Oxygen co-doping analysis

Since the excitation of erbium ions stems from the same physical mechanism both in electroluminescence and in photoluminescence [6], to determine the proper oxygen co-doping dose, we perform a photoluminescence characterization of three different silicon samples. Specifically, in our analysis the same Er dose is adopted, varying the O one. The erbium dose is equal to 1.0e13 Er/cm^2 whereas the oxygen doses are equal to a) 3.5e13 O/cm^2 b) 7e13

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O/cm^2 and c) 1.4e14 O/cm^2. In Fig.2 the photoluminescence at 11 K of the three samples is present. It is evident that the oxygen co-doping has a dramatic impact on the erbium photoluminescence at cryogenic temperature. Since our devices are supposed to work both at 300 K and at 77 K, we opt for the highest possible oxygen dose in our p-n junctions.

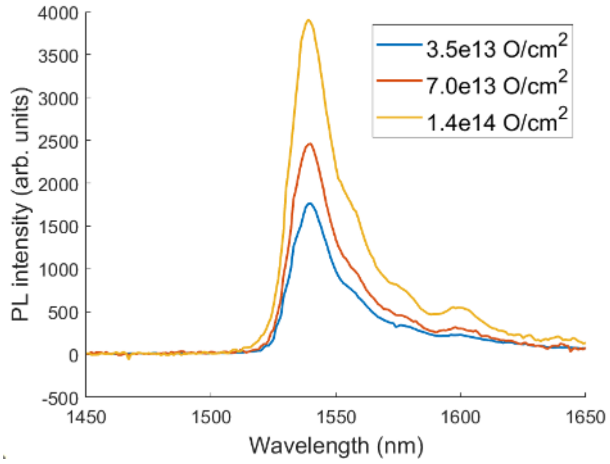

Figure 2. Here are presented the photoluminescence signals at 11K for three flat silicon samples doped with the same erbium dose (1.0e13 Er/cm^2) but with three different oxygen doses. All the samples were annealed for 30 minutes at 900°C.

3 Device fabrication

The devices are fabricated through a top-down process performed by a combination of electron beam lithography, reactive ions etching, electron beam physical vapor deposition and ion implantation starting. The entire process is performed on a 220 nm thick Si layer on a 2 μm thick SiO_2 buried oxide layer . The first step is the definition of the mesa structure, followed by the doping of the n area with phosphorus, of the p area with boron as well as of the optically active zone, in the center of the device, with erbium and oxygen. All the dopants are introduced by ion implantation and activated with a rapid thermal annealing processes. The final step is the definition of the two gold contacts on top of the n and p regions. Three samples are fabricated and characterized, they differ from each other by the size of the erbium doped area: in the first device it is equal to 1 μm × 1μm (Fig. 1), in the second one to 15 μm × 15μm and in the last one to 50 μm × 50 μm.

4 Optical characterization

All the samples are characterized at room temperature by imposing a current and collecting the electroluminescence signal. To reduce the background noise, superconducting nanowires detectors working at cryogenic temperature are employed and the integration time was set equal to one second. The signals from the three different devices are shown in Figure 3. They are approximately comparable in spite of the different erbium doped areas as the detection region is imposed by the collecting fiber which is around 5 μm^2. The highest signals refer to the two smallest junctions, which suggests that the photons in those structures are better directed toward the collecting fiber. A clear hint that the detected signals are due to the erbium ions is that moving away from the erbium doped areas, the signals drop dramatically.

From the previous measurements, it is possible to compute the number of photons emitted by each erbium ion in one second. Considering that we estimate that a tenth of erbium ions is lost after the rapid thermal annealing [7] and that the optical throughput of the setup is approximately 0.1%, a value equals to 50 is obtained in the case of the 1 μm × 1μm device when a current of 50 μA is imposed.

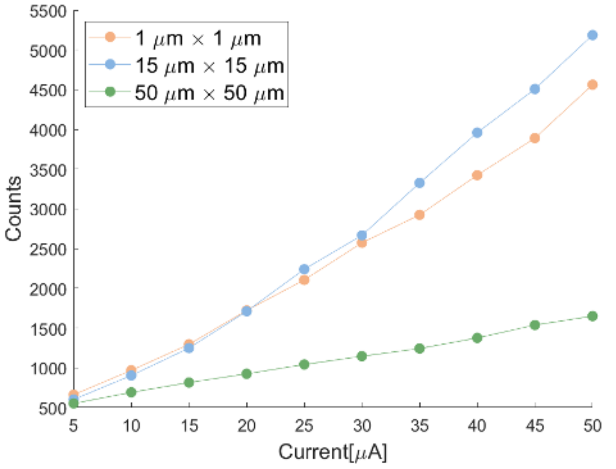

Figure 3. The photon counts obtained for each device imposing a current in the range 5-50 μA. The integration time is equal to one second and the resulting dark counts are around 400.

5 Conclusions

A weak photon source operating at 1550 nm using a silicon diode implanted with erbium and oxygen is presented. We determine the proper oxygen co-doping dose to obtain a significant enhancement of the Er electroluminescence signal at low temperature.

6 Acknowledgement

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References

[1] F. Cavaliere, E. Prati, L. Poti, I. Muhammad, T. Catuogno, Quantum Reports **2(1)**, 80-106 (2020)

[2] M. Avesani et al., npj Quantum Information **7(1)**, 1-8 (2021)

[3] G. Foletto, F. Picciariello, C. Agnesi, P. Villoresi, G. Vallone, Physical Review A **105(1)**, 012603 (2022)

[4] M. Di Giancamillo, P. Biagioni, V. Sorianello, E. Prati, EPJ Web of Conferences **255**, EOSAM21 (2021)

[5] F. Priolo, G. Franzò, S. Coffa, A. Carnera, Physical Review B **57(8)**, 4443 (1998)

[6] G. Franzò, F. Priolo, S. Coffa, A. Polman, A. Carnera, Applied Physics Letters **64(17)**, 2235-2237 (1994)

[7] M. Celebrano, L. Ghirardini, M. Finazzi, Y. Shimizu, Y. Tu, K. Inoue, Y. Nagai, T. Shinada, Y. Chiba, A. Abdelghafar, M. Yano, T. Tanii, E.Prati, Optics Letters **42**, 3311-3314 (2017)