Supplementary information

Activation of telecom emitters in silicon upon ion implantation and ns pulsed laser annealing

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Supplementary Note 1. Laser annealing effects at varying ion implantation fluence

The trend of the ZPL intensity of both the G- and the W-center as a function of the lasing energy density, as shown in Fig. 2 of the main text, exhibits a maximum value at a specific pulse energy of 0.76 mJ/cm^2 and 0.69 mJ/cm^2, respectively. To assess whether these energy density values depend on the ion implantation fluence, i.e. whether the density of absorption centers introduced by radiation damage, plays a relevant role in the local increase of the substrate temperature, the following experiment was performed. A sample based on the same substrate wafer was implanted at a different C ion fluence (namely, 8×10^{14} cm^{-2} rather than the 2×10^{14} cm^{-2} value discussed in the main text). The same laser processing was performed following the ion implantation. The results on the ZPL intensity are shown in Figure S1 below, to be compared with those reported in Fig. 2a and 2b for the G center and the W center, respectively.

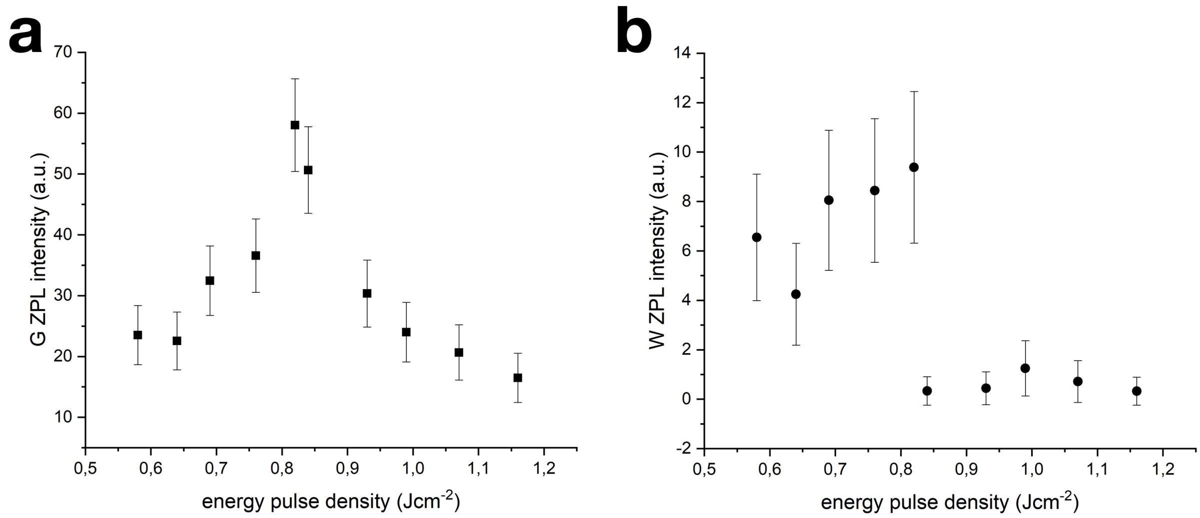

Figure S1: ZPL intensity of **a)** G center (1279 nm), and **b)** W-center (1218 nm) as a function of the ns lasing energy density in a silicon wafer implanted with 8x10^{14} cm^{-2} C at 36 keV energy.

The hypothesis that the ion fluence is a relevant factor in the laser radiation absorption would imply a decrease of the energy pulse density at which the G- and W- center ZPL intensity maxima are observed, since the implantation fluence is increased. Conversely, the data show a similar trend to what shown in Fig. 2 of the manuscript, with a minimal shift in the cutoff value centered at 0.8 mJ for the W center and 0.85 for the G center (to be compared with the 0.76-0.82 mJ cm^{-2} range reported for the $2x10^{14}$ cm^{-2} fluence). We do not regard this slight difference as significant, as it could be explained in terms of a minimal discrepancy in the focusing conditions of the lasing system. We thus interpret these additional results as a confirmation that the energy delivered to the sample is entirely absorbed by the silicon substrate. The independence of the cutoff values can be explained by considering that the ion fluence values adopted here are not sufficient to induce any amorphization or phase transition in the material, and that the local density of defects produces a negligible change in the absorption coefficient of the material at the considered lasing wavelength.

Supplementary Note 2. Optical sensitivity of the photoluminescence setup

We discuss in details estimated the maximum emission intensity expected from a single G center in our experimental setup, assuming the lack of non-radiative relaxation paths as the reciprocal of the emission lifetime (3.8 ns [1], Ref. 2) and considering the following experimental collection efficiencies (a scheme of the setup is given in **Fig. S2**):

- A photon extraction efficiency due to total internal reflection of 2% [2]
- A transmittance of the confocal microscope objective of 1% (Zeiss EC Epiplan-Neofluar 100x/0.9 BD DIC M27,.FWD=1.0mm). The transmittance curve declared by the supplier is limited to 1200 nm (~50% transmittance). The transmittance at the G-center emission wavelength was measured using a 1277 nm laser, thus confirming that the objective is optimized for the visible range.
- A 97% optical transmittance of the optical windows of the cryostat;
- A 0.22 NA of the optical fiber exploited for photon collection;
- A 97% transmittance of the optical filters and elements;
- A 93% transmittance of the dichroic mirror of the confocal microscope;
- A 20% detection efficiency of the InGaAs single-photon detector;
- A measured 5% efficiency of the monochromator exploited for the spectral analysis, due to the coupling of both the entrance and exit windows with a 0.22 NA optical fiber, in addition to the optical losses associated with the diffraction grating.

The maximum expected count rate (i.e. the integrated counts in the PL spectrum) from single-photon emitting G centers is thus ~1030 cps.

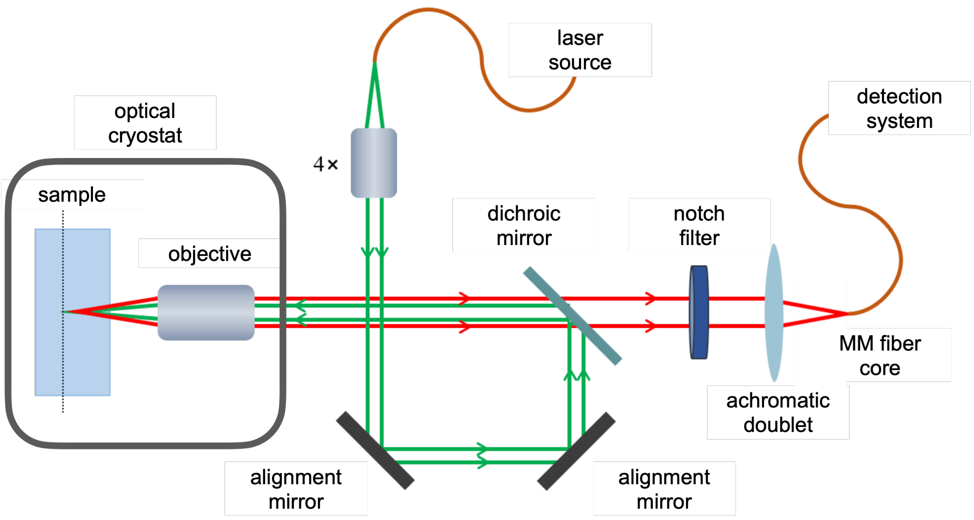

Figure S2: sketch of the main optical elements composing the experimental photoluminescence setup adopted in this work

Supplementary Note 3. Considerations on the formation yield of the G-center

The formation yield of an optical center upon ion implantation is commonly defined as the ratio between the areal density of fabricated optically active emitters centers and the ion fluence, i.e. the number of color centers formed upon the implantation of an individual ion [3].

However, this definition does not apply straightforwardly to this experimental scenario. To properly understand this, it should be noted note that Refs. [4–7] describe C implantation in silicon-on-insulator (SOI) with unspecified doping concentration. Thus, the relation between the number of implanted ions and the number of G centers fabricated in the substrate is not biunivocal, since a non-negligible fraction could originate from the coupling of native C with radiation-induced vacancies. Furthermore, it is worth remarking that the definition of formation efficiency in the case of C and proton co-implantation (e.g. Ref [1]) is far from being considered straightforward.

Also, Ref [8] highlights the fact that the RTA treatment adopted in most of the cases purposedly aims at lowering the formation efficiency of the G center, in order to achieve a sufficiently low areal density of G centers for single-photon emitter identification.

In addition, it is worth stressing that none of the aforementioned works explores the formation of the G center in float-zone Si, denoted by native C concentration lower than 1×10^{16} cm^{-3}.

Despite the above-mentioned variability in the experimental conditions, we offer our best insight in the complex matter of formation efficiency by providing our formation efficiency estimates on the basis of the data discussed in **Section S2**.

The integration of the PL spectrum in Fig. 2 from the most intense (i.e., 0.76 mJ cm^{-2}) corresponds to 280 kcps, indicating the formation of ~280 centers (~1 kcps from each, as stated in **Sect. S2**) within the probed surface of the confocal microscope (roughly 1 μm^2). The achievement of such surface density with the implantation of C ions at 2×10^{14} cm^{-2} fluence corresponds to a formation efficiency of 1.4×10^{-4}. Please note that this estimate is significantly affected by the additional assumption that no shelving state is involved in the G center emission. This value might be compared with the formation efficiency of 1.6×10^{-7} inferred from [5] considering an areal density of 0.08 centers μm^{-2} following C implantation at 5×10^{13} cm^{-2} fluence and subsequent 5 s rapid thermal annealing. As previously mentioned, however, this value should be taken with a grain of salt, since the efficiency was lowered on purpose by the authors to enhance the chance of identifying individual emitters.

Conversely, the formation efficiency we found is in line with the value of 2×10^{-4} reported in Ref. [7], where the co-implantation of protons and C ions (the latter at ~1×10^{11} cm^{-2} fluence) is exploited to achieve an areal density of 0.2 μm^{-2}.

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