



**HAL**  
open science

## Femtosecond laser induced creation of G and W-centers in silicon-on-insulator substrates

Hugo Quard, Mario Khoury, Andong Wang, Tobias Herzig, Jan Meijer,  
Sébastien Pezzagna, Sébastien Cueff, David Grojo, Marco Abbarchi, Hai Son  
Nguyen, et al.

► **To cite this version:**

Hugo Quard, Mario Khoury, Andong Wang, Tobias Herzig, Jan Meijer, et al.. Femtosecond laser induced creation of G and W-centers in silicon-on-insulator substrates. *Physical Review Applied*, 2024, 21 (4), pp.044014. 10.1103/PhysRevApplied.21.044014 . hal-04066124

**HAL Id: hal-04066124**

**<https://hal.science/hal-04066124>**

Submitted on 11 Apr 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

# Femtosecond laser induced creation of G and W-centers in silicon-on-insulator substrates

Hugo Quard<sup>1,\*</sup>, Mario Khoury<sup>2</sup>, Andong Wang<sup>3</sup>, Tobias Herzig<sup>4</sup>, Jan Meijer<sup>4</sup>, Sébastien Pezzagna<sup>4</sup>, Sébastien Cuffé<sup>1</sup>, David Grojo<sup>3</sup>, Marco Abbarchi<sup>2,5,†</sup>, Hai Son Nguyen<sup>1,6</sup>, Nicolas Chauvin<sup>1</sup>, and Thomas Wood<sup>1</sup>

<sup>1</sup>*Ecole Centrale de Lyon, INSA Lyon, Université Claude Bernard Lyon 1, CPE Lyon, CNRS, INL, UMR5270, 69130 Ecully, France*

<sup>2</sup>*Aix Marseille Univ, CNRS, Université de Toulon, IM2NP, UMR 7334, F-13397 Marseille, France*

<sup>3</sup>*Aix-Marseille University, CNRS, LP3, UMR7341, 13009 Marseille, France*

<sup>4</sup>*Division of Applied Quantum Systems, Felix-Bloch Institute for Solid-State Physics, University Leipzig, Linnéstrasse 5, 04103 Leipzig, Germany*

<sup>5</sup>*Solnil, 95 Rue de la République, 13002 Marseille, France and*

<sup>6</sup>*Institut Universitaire de France (IUF)*

(Dated: April 11, 2024)

The creation of fluorescent defects in silicon is a key stepping stone toward assuring the integration perspectives of quantum photonic devices into existing technologies. Here we demonstrate the creation, by femtosecond laser annealing, of W and G-centers in commercial silicon on insulator (SOI) previously implanted with  $^{12}\text{C}^+$  ions. Their quality is comparable to that found for the same emitters obtained with conventional implantation processes; as quantified by the photoluminescence radiative lifetime, the broadening of their zero-phonon line (ZPL) and the evolution of these quantities with temperature. In addition to this, we show that both defects can be created without carbon implantation and that we can erase the G-centers by annealing while enhancing the W-centers emission. These demonstrations are relevant to the deterministic and operando generation of quantum emitters in silicon.

## I. INTRODUCTION

Point defects in silicon have been intensively studied over the past few years for the creation of silicon-based quantum devices [1]. Quantum light sources are key devices that are potentially exploitable for quantum computing, quantum networks or for the implementation of quantum cryptography protocols. Thanks to the device-friendly environment, single-photon sources and spin-photon interfaces could be readily integrated within existing electronic and photonic platforms.

Among all the different optically-active defects in silicon [2–10], two that are often studied are W [11–16] and G-centers [1, 17–35]. W-centers are composed of three interstitial Si atoms and recent theoretical works have revealed that these defects probably have a  $I_3\text{-V}$  configuration [36]. The optically active form of a G-center is made of two C atoms in substitutional sites linked to an interstitial Si atom [17] as represented in Fig.1(a).

Numerous procedures can be used to fabricate W or G-centers such as silicon [12] or carbon implantation followed by a proton irradiation [22, 37], electron irradiation [3], focused-ion-beam (FIB) implantation [8], pulsed ion beams [38], and reactive ion etching [39, 40]. All these methods involve the use of ion implanters or accelerators. They are relatively bulky and expensive approaches that require several steps (e.g. for G-centers: carbon implantation, annealing, and proton implantation) in order to create a light emitter. Furthermore,

the most advanced methods using focused ion beams [8] are intrinsically stochastic and the number of quantum emitters per ion impact is not precisely controlled.

A further method, that can be used to create point defects, is laser annealing also called laser doping. The use of a laser has been shown to be a viable approach for integrating quantum emitters in Si grown by the float-zone method [41], in  $\delta$ -doped Si [42] or in p-doped Si [43]. Both W and G-centers can be obtained in p-doped Si [16] as well as in n-type Si implanted with  $^{29}\text{Si}^+$  ions [2]. However, the creation of these defects has usually been unintentional, induced with laser pulses longer than 4 ns and in bulk Si substrates.

In this paper we address the creation of W and G-centers by femtosecond laser annealing, with the process being investigated for the first time on SOI substrates, taking both C-doped and pristine SOI wafers as starting points. The quality of these defects is confirmed by continuous-wave (cw) and time-resolved photoluminescence (PL) measurements. The temperature dependence of the emitters, their broadening and lifetimes are comparable to those reported with standard fabrication methods, accounting for the high quality of our approach based on femtosecond laser pulses. We also demonstrate that the C-implantation step is not necessary to create the light emitters. Finally, by low temperature annealing, we can selectively erase the G centers while improving the brightness of the W center emission.

---

\* hugo.quard@insa-lyon.fr

† marco.abbarchi@im2np.fr

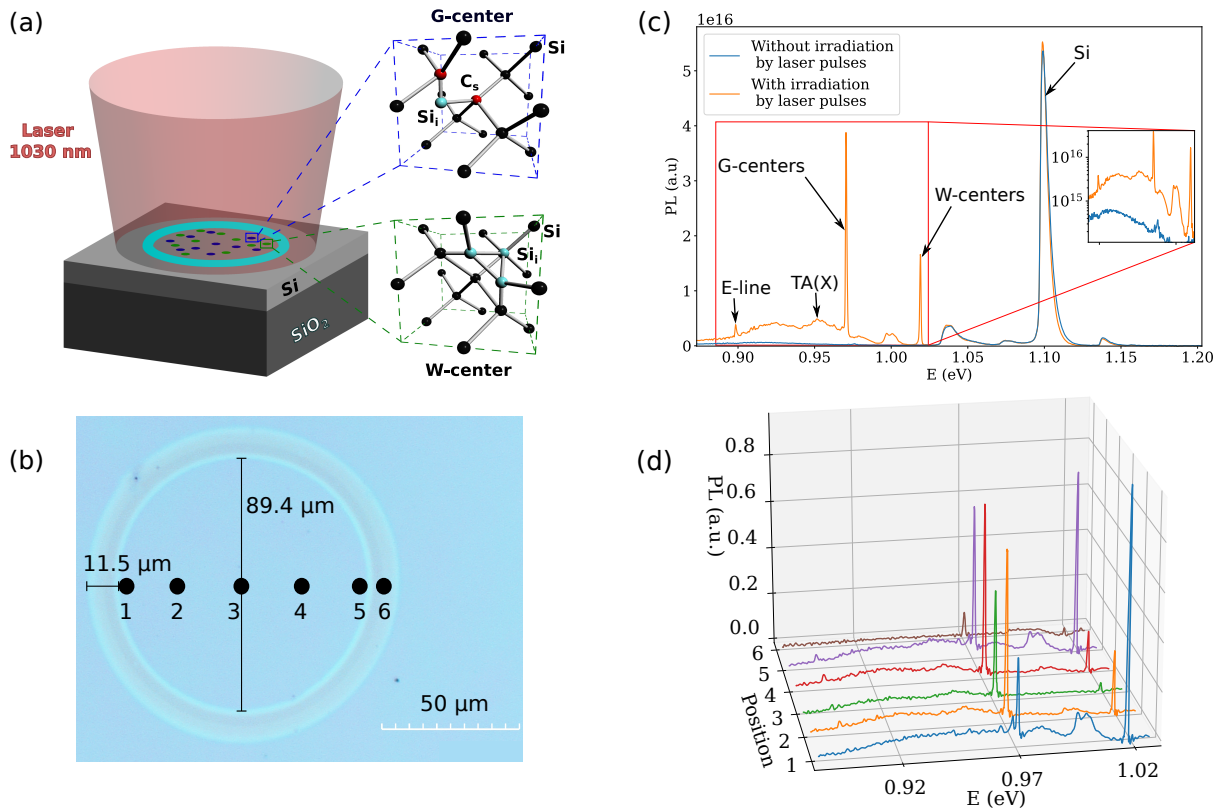


FIG. 1. (a) A schematic representation of the laser irradiation process used to create G and W-centers. (b) An optical microscope image of an area irradiated with 3 pulses having an energy of  $218 \mu\text{J}$ . (c) A comparison of the macro-PL spectra at 12K of an area not irradiated by laser pulses and an area irradiated by 3 pulses. (d) A comparison of the micro-PL spectra at 11K of the different positions noted on the optical microscope image and corrected by the background spectra obtained with non-annealed SOI (see the Supplementary Information [44] for the correction applied).

## II. SAMPLE DESCRIPTION AND EXPERIMENTAL SETUP

The samples are SOI wafers featuring a 220 nm top silicon layer and a 2 μm buried oxide layer, some of which were implanted with  $^{12}\text{C}^+$  ions. The beam energy was set to 34 keV in order to implant the carbon ions halfway into the top silicon layer and two different fluences were explored, namely  $1 \times 10^{12}$  and  $1 \times 10^{13}$  ions/cm<sup>2</sup>. The implantation was followed by a flash annealing under an N<sub>2</sub> atmosphere for 20 s at 1000°C, to remove lattice damage [37].

The samples were then irradiated by laser pulses focused with a 750 mm planoconvex lens under ambient conditions, differing from location to location by the number of pulses used (from 1 to 5) and by the energy of the pulses (95, 143, 175 and 218 μJ), to supply the energy necessary to reorganize the crystal lattice and create emitting defects in silicon. This step is schematically represented in Fig.1(a). The Gaussian laser beam used was centered at 1030 nm, with pulses of a duration less than 200 fs. The waist of the beam was  $w_0 = 178 \mu\text{m}$  and the repetition frequency of the pulses was 1kHz. The

samples were created in pairs, sharing the same carbon implantation parameters, of which only one of the two underwent a second annealing under an N<sub>2</sub> atmosphere for 5 min at 125 °C after the laser annealing.

The PL measurements were performed at low temperature, the samples being cooled down with a closed-cycle helium cooled cryostat. For the macro-PL measurements, the optical pumping was performed with a continuous wave laser diode at 405 nm focused onto the sample with a spot diameter of  $\approx 75 \mu\text{m}$ . A Cassegrain objective was used to collect the PL emission with a numerical aperture between 0.15 and 0.4. For the micro-PL measurements, the optical pumping was performed with a 780 nm diode-pumped solid-state laser. The signal was detected in a confocal configuration with a microscope objective (NA=0.4) allowing a spot diameter of  $\approx 10 \mu\text{m}$  for the pump. In both cases, the collected signal was dispersed by a spectrometer and detected by a liquid nitrogen-cooled InGaAs detector enabling spectral detection from 900 to 1600 nm. For the time-resolved PL, a 515 nm laser emitting 200 fs pulses and a 54 MHz repetition rate was used for the optical pumping and the detection was performed with an InGaAs photodiode.

### III. RESULTS

#### A. Creation of G and W-centers

For the highest pulse energy investigated (218  $\mu\text{J}$ ), the laser pulses created a ring visible under an optical microscope at the surface of the irradiated parts of the sample around the point of impact of the laser beam, as shown in Fig.1(b). The creation of this circle is specific to the ultrafast quenching conditions accessible with femtosecond laser irradiation. It results from the melting of the top layer of Si which resolidifies in different states due to the temperature gradient which spatially varies the solidification kinetics. The ring corresponds to amorphous Si, whereas the central part is constituted of recrystallized Si [43, 45]. The outer contour of the ring shown in Fig1 (a) corresponds to a local fluence of about 330 mJ/cm<sup>2</sup> that matches well with the measured threshold for Si surface amorphization in a previous work using the same laser [46].

The PL signal from these areas reveals the creation of both G and W-centers, as shown by the orange curve in Fig.1(c), exhibiting the zero phonon lines (ZPLs) of the two emitters, at 1.019 eV for W-centers and 0.97 eV for G-centers, as well as their typical phonon sidebands [3, 22, 36].

On the same sample, we also collected the PL emission in areas that were not targeted by the laser (blue curve in the Fig.1 (c)). The corresponding spectrum exhibits only the typical Si signal at 1.1 eV, accompanied with the relative phonon sidebands.

For lower laser fluences, the ring is not observed (Supplementary Information [44]) and there is a lack of PL emission from W- and G-centers, suggesting the crucial role of the melting and recrystallization steps in rearranging the atoms to form the emitters.

We also studied the influence of the number of pulses on the intensity, the position and the width of the ZPLs (Supplementary Information [44]). No trend can be seen from one sample to another, which suggests that at each pulse there is melting of the silicon and therefore the destruction of preexisting defects. New defects are then created during recrystallization.

#### B. Spatial distribution of G and W-centers

To investigate the distribution of centers within the recrystallized region, micro-PL measurements were conducted. The spectra, adjusted for background PL originating from the SOI wafer itself, are presented in Fig. 1(d). The original micro-PL spectra and details regarding the correction procedure are provided in the Supplementary Information [44]. Fig. 1(d) unveils notable differences in the distribution of the G and W centers. Notably, the signal of W-centers appears brighter near the amorphous ring (positions 1 and 5 in Fig. 1(b), (d)) compared to the center of the recrystallized area (position

3). It is known that there is a strong dependence between the concentration of self-interstitial clusters and the cooling rate during the Si recrystallization [16]. Therefore, it is not surprising to observe a strong modification of the W-center emission intensity from the center to the border of the recrystallized area. In contrast, G-centers exhibit a more random distribution within the recrystallized area, reflecting the random distribution of carbon throughout the sample. Supplementary Information [44] includes a graph depicting the maxima of the ZPLs of both centers with regard to their position.

Micro-PL measurements on the amorphous ring (position 6 in Fig1(b)) reveal significantly weaker signals for G and W-centers compared to the signals obtained in the recrystallized area (Fig1(d)). We attribute these signals to defects located in proximity to the edge of the amorphous ring.

#### C. Influence of the carbon fluence

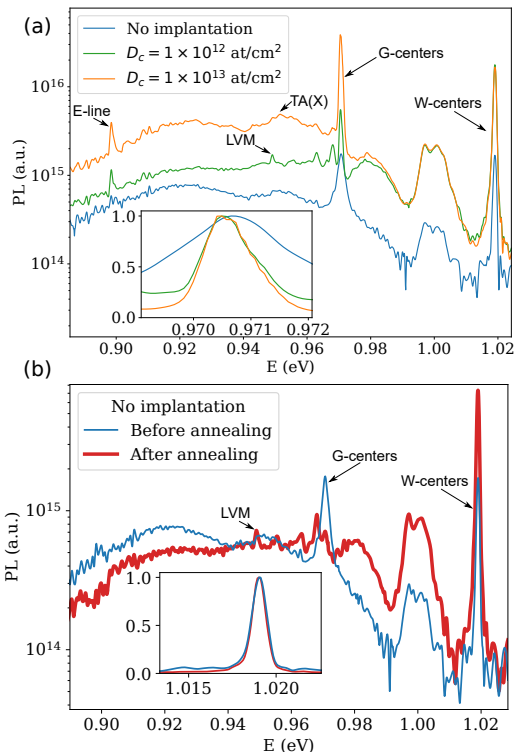


FIG. 2. All the spectra were measured at 12 K with excitation by a laser diode at 405 nm. (a) The macro-PL spectra obtained for samples irradiated by 3 laser pulses with an energy of 218  $\mu\text{J}$ . Each sample is differentiated by the fluence of implanted carbon  $D_C$ . The inset represents the normalized ZPL of G-centers. (b) A comparison between the macro-PL spectra obtained for two samples irradiated by 3 laser pulses with an energy of 218  $\mu\text{J}$ . The two samples have not undergone carbon implantation and one of them underwent a second annealing under N<sub>2</sub> atmosphere for 5 min at 125°C. The inset represents the normalized ZPL of the W-centers.

In this section we focus on the influence of the fluence of implanted carbon on the PL of the centers. In Fig.2(a), we present the macro-PL spectra of three samples that differ by virtue of the carbon fluence used during the implantation. For each spectrum the Si signal is of the same order of magnitude which allows a direct comparison between the spectra.

The ZPL intensity of the G-centers increases when increasing the carbon fluence, which is consistent with previous findings [37] for emitters created after proton irradiation.

For pristine samples (i.e., no carbon implantation), the signals of the G- and W-centers appear with an amplitude that is about an order of magnitude lower with respect to their implanted counterparts. We interpret the creation of G-centers in carbon-free samples as an effect of incorporation of residual C present in small quantities in the native oxide (e.g. unintentionally deposited after the manufacturing process of the SOI wafer). We have verified that by oxidation of the Si in a rapid thermal process before the laser annealing, the signal from G-centers disappears, confirming that the C contamination comes from impurities in the native oxide and that can be efficiently passivated by thermal oxidation (see Supplementary Information [44]).

As for the W-centers, this result shows that the implantation step disrupts the crystalline organization and creates more interstitial Si. However, even if defects are created in smaller numbers in the pristine sample, they have the same optical properties as those obtained with the implantation step, namely, a ZPL with the same full width at half maximum (FWHM) (see Supplementary Information [44]), since the creation process of W-centers is the same in both cases. In contrast, for G-centers, the creation process differs due to the origin of the C, resulting in a broadening and a slight blue shift of the ZPL of the non-implanted sample, as depicted in Fig. 2(a).

#### D. Effect of a 5 min annealing at 125°C

We now investigate the effect of a 5 min annealing at 125°C on the PL signal of these laser-created emitting centers. After annealing, non-implanted samples display only W-center emission that is enhanced by a factor of four with respect to non-annealed samples whereas that of G-centers disappears (Fig.2(b)). Moreover, the FWHM of the ZPL of W-centers is not modified by the treatment as shown in the inset of Fig2(b). The increase in the W-center PL emission has been reported by several groups after annealing in the 100 - 200°C range [47–50]. This is explained by the annealing-induced breaking of Si self-interstitial ( $\text{Si}_i$ ) clusters, leading to the migration of these  $\text{Si}_i$ , which are potentially captured by remaining clusters. Consequently, the annealing alters the cluster size distribution, resulting in an increased number of 3  $\text{Si}_i$  clusters (W-centers). Moreover, the migration of  $\text{Si}_i$  could account for the disappearance of the G-centers

emission. According to Davies and Kun [51]  $\text{Si}_i$  may be captured by G-centers, forming new complexes.

The annihilation of G-centers after an annealing is also observed for carbon implanted samples and the resulting spectrum is comparable to that obtained for pristine samples when normalized by the maximum of the ZPL of W-centers. Therefore, we demonstrate that we can create and isolate W-centers without any implantation step with optical properties comparable to those obtained with implantation.

#### E. Recombination dynamics of G-centers

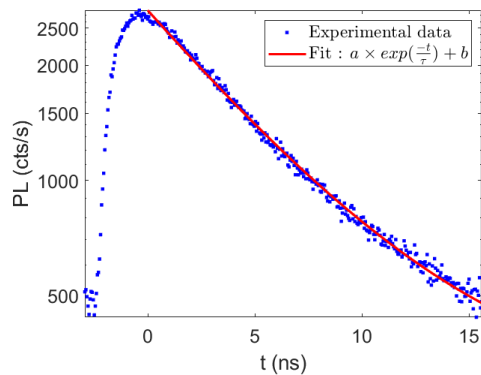


FIG. 3. The time-resolved PL signal obtained at 12 K with a pulsed laser at 515 nm with a shortpass filter in energy (0.99 eV) to eliminate the contribution of the ZPL of W-centers and a large part of their phonon sideband. The experimental data (blue points) are fitted by a mono-exponential function adjusted by a constant  $b$  (red curve).

We have performed time-resolved PL measurements on the brighter sample, namely the sample with the highest fluence of C implanted, filtering the PL signal with a short-pass filter at 0.99 eV to eliminate the major contribution of W-centers (Fig.3). The PL decay is well fitted by a mono-exponential function (plus a constant) providing a characteristic lifetime of 5.9 ns, which is consistent with conventional G-centers obtained by co-implant of carbon and proton irradiation for which the lifetime is about 5-6 ns [22, 33]. Therefore, G-centers created with both protocols have the same excited state lifetime. As the radiative yield of G-centers is less than 10% at 30K [33], the measured decay rate is strongly related to non-radiative channels even at cryogenic temperatures.

The constant used to adjust the fit is ascribed to the contribution of a longer decay time corresponding to the phonon-sideband of the W-centers: these defects have lifetimes ranging from 3 ns to 30 ns [36]. Owing to our excitation pulses being repeated every 18 ns, an overlap of the PL decays coming from the phonon-sideband of W-centers can contribute to the time resolved spectra. We therefore cannot measure the lifetime of W-centers.



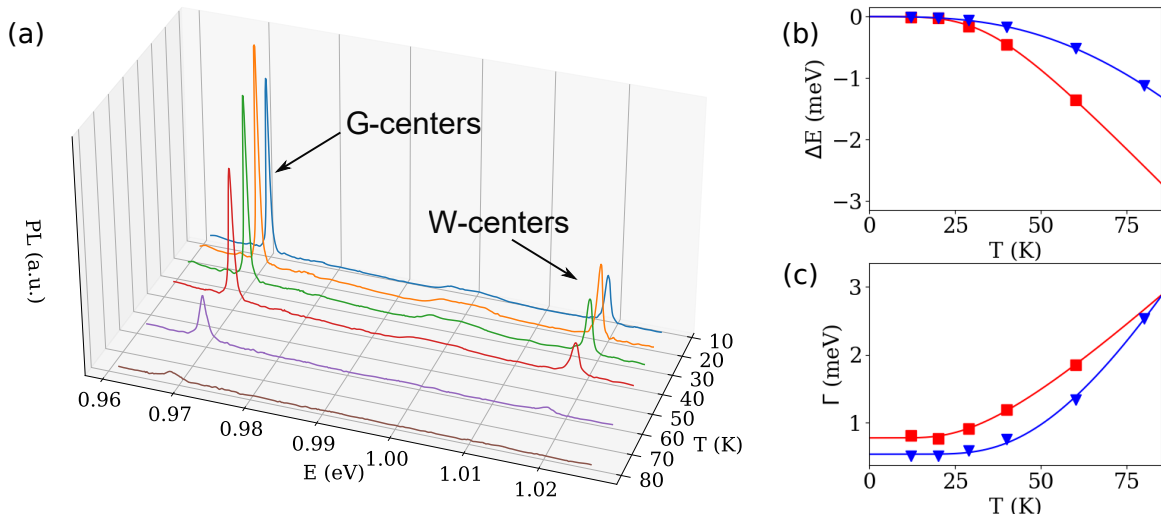


FIG. 4. **(a)** Temperature-dependant macro-PL spectra centred around the ZPLs of G and W-centers in the range of temperature from 12 K to 80 K. **(b)** Variation of the energies at the center of the ZPLs of G-centers (blue triangles) and W-centers (red squares) as a function of temperature. The symbols represent the experimental data and the lines the fits given by the equation (1). The fitting parameters are  $E_{0W} = 1018.69 \pm 0.02$  meV,  $\alpha_W = 0.06 \pm 0.01$  meV/K,  $\Theta_W = 76 \pm 15$  K, and  $P_W = 4.2 \pm 1.1$  for the W-centers and  $E_{0G} = 970.194 \pm 0.003$  meV,  $\alpha_G = 0.07 \pm 0.01$  meV/K,  $\Theta_G = 186 \pm 29$  K, and  $P_G = 3.0 \pm 0.1$  for the G-centers. **(c)** The evolution of the FWHM of the ZPLs of G-centers (blue triangles) and W-centers (red squares) as a function of temperature. The symbols represent the experimental data and the lines the fits given by the equation (2). The fitting parameters are  $\Gamma_{0W} = 0.78 \pm 0.03$  meV,  $a_W = 5 \pm 1$  meV, and  $\Omega_W = 9 \pm 1$  meV for the W-centers and  $\Gamma_{0G} = 0.54 \pm 0.03$  meV,  $a_G = 20 \pm 5$  meV, and  $\Omega_G = 17 \pm 1$  meV for the G-centers.

### F. Temperature dependence of the ZPL

The ZPL energy as a function of temperature is represented in Fig.4(b). The experimental data are fitted with an expression proposed by Pässler [52]:

$$\begin{aligned} \Delta E(T) &= E_{ZPL}(T) - E_0 \\ &= -\frac{\alpha\Theta_p}{2} \left[ \sqrt[1+p]{1 + \left(\frac{2T}{\Theta_p}\right)^p} - 1 \right] \end{aligned} \quad (1)$$

where  $E_0$  (meV) is the limit of the ZPL energy when  $T \rightarrow 0$  K,  $\alpha$  (meV/K) is the slope of the curve, namely the entropy, for  $T \rightarrow \infty$ ,  $\Theta_p$  (K) is the average temperature of the phonons and  $p$  is a dimensionless parameter.

The thermal redshift for W-centers evolves proportionally to  $T^4$  [53] whereas for G-centers to  $T^3$ , consistent with previous observations [22]. These fits provide the average temperature of the phonons coupled with the defects. If we convert the obtained values to energies we find  $E_{phW} = 7 \pm 1$  meV for W-centers and  $E_{phG} = 16 \pm 2$  meV for G-centers. For the latter, the energy obtained is close to that of TA phonons at the X point of the Brillouin zone [9], namely 20 meV. Therefore we conclude that the defect coupled preferentially with TA(X) phonons. As for W-centers, the obtained value does not correspond to a typical phonon energy in silicon and it is lower than the TA(X) energy. A possible explanation for this observation will be given in the following paragraphs.

In Fig.4(c), we present the FWHM of the ZPLs as a

function of temperature. The experimental data are well fitted by the following model that describes the broadening of a ZPL with heating [54]:

$$\Gamma = \Gamma_0 + a \left[ \exp\left(\frac{-\Omega}{k_B T}\right) - 1 \right]^{-1} \quad (2)$$

where  $\Gamma_0$  is the zero-temperature limit of the FWHM and the second term accounts for the coupling between the phonons and the emitters,  $a$  represents the intensity and  $\Omega$  the typical energy of this coupling.

The zero-temperature limit obtained for G-centers with our procedure, namely  $\Gamma_{0G} = 0.54 \pm 0.03$  meV, is of the same order of magnitude as that obtained for an ensemble of G-centers created by proton irradiation ( $0.3 \pm 0.03$  meV) [22]. The slightly larger value obtained in our case can be explained by the simultaneous presence of G-centers and Si self-interstitials which could slightly broaden the signal obtained for the ensemble of defects.

For ensembles of W-centers, to date, no study has been conducted for ZPL broadening. The study of individual W-centers [32] has shown a zero-temperature limit below 0.1 meV. However, the energy differences between the ZPLs from one defect to another are within 1 meV owing to local variations in the emitter environment. Therefore, the value of  $\Gamma_{0G} = 0.78 \pm 0.03$  meV that we have obtained is consistent with single defect investigation when taking into account the ZPLs' dispersion in energy.

For G and W-centers, the typical energies  $E_{ph}$  and  $\Omega$  that we have obtained with the fits of the broadening

and the redshift of ZPLs overlap, taking uncertainties into account. This allows us to give a probable explanation for the low value obtained for  $E_{phW}$ . Indeed, the typical energy obtained with the fit of the broadening ( $\Omega_W$ ) could also be interpreted as the activation energy of the excitonic transition to the first excitonic state from the ground-state [55], which could explain why we obtain a value lower than the typical energy of phonons in Si.

#### IV. DISCUSSION

The relevance of our work lies in the possibility of deterministically creating at least one quantum emitter in Si: in analogy with SiC and diamonds, femtosecond laser pulses can, in principle, be used to form the emitters *in situ* and *operando*, while monitoring the emission from newly formed defects on a pulse-by-pulse basis [56, 57]. This method also allows us to reduce the area of creation of the emitters down to the size of the laser spot, as shown in Fig.1, which demonstrates that the emitting centers are created only in the irradiated areas. Even if we do not reach the precision of FIB, this method is cheaper and easier to implement which is promising for the large-scale creation of emitters. Moreover we have demonstrated that W and G-centers created in C-implanted Si have optical properties and recombination dynamics that are adequate when compared with the literature, which proves that we have obtained emitters with the same quality as those obtained by other fabrication methods.

We have also demonstrated that the implantation step is not necessary to create W and G-centers, as we have collected the PL signature of both centers from pristine samples. Such samples contain only residual carbon incorporated in the surface native oxide on the SOI after the manufacturing of the wafer, which implies a low concentration of carbon. This leads to the creation of low-density G-centers, which is confirmed not only by the low intensity of the ZPL of G-centers but also by its broadening and blue-shift compared to the implanted samples (see inset of Fig.2). Indeed Zhiyenbayev *et al.* have demonstrated that the increase of internal strain due to a high fluence of implanted carbons leads to a redshift the ZPL of G-centers and reduces their inhomogeneous broadening [35]. As for W-centers, they have the same optical properties in implanted and non-implanted samples. We have demonstrated a way to annihilate G-centers while slightly enhance the PL of W-centers by carrying out an annealing at 125°C during 5 min. This phenomenon is opposite to what was expected, since it has been demonstrated that the intensity of the ZPL of G-centers created with carbon implantation followed by proton irradiation can be increased by a factor of 8 with such thermal treatment [21]. It is worth noting that in the sample of Berhanuddin *et al.* only G-centers were created whereas in our case we have both W and G-centers which could explain the difference in behavior of G-centers.

#### V. CONCLUSION

In this paper, we have demonstrated for the first time the creation of G and W-centers simultaneously in carbon-implanted SOI by femtosecond laser annealing. The quality of these defects are comparable to those obtained by the usual, well established methods in the literature. We have also demonstrated that we can create G and W-centers without any implantation step. However, G-centers created with this method have a ZPL broader than those obtained with carbon implantation. Furthermore, we have demonstrated that an annealing at low temperature annihilates G-centers while slightly enhancing the PL emission of the W-centers. Therefore, we have proved that we can create and purify W-centers of good quality without any implantation steps, which allows us to create W-centers at low cost, on-demand and in a restricted area of a size close to the cross section of the laser spot. This represents a step forward for the deterministic creation of W-centers in photonic structures. Indeed, with this method it is possible to precisely position the defects in the structures and it is also conceivable to have control over the density of defects created by studying in more detail the influence of the number of pulses and their energy. This last aspect could even lead to the study of single emitters, assuming that we manage to create the W centers in sufficiently low density.

Note added: We recently became aware of a paper by Jhuria *et al.*, wherein they have demonstrated the creation of both centers using femtosecond laser pulses. However, they have employed significantly different experimental parameters, including shorter pulses, a different wavelength, and a p-type SOI substrate [58].

*Acknowledgement:* This research was funded by the European Union (EU) Horizon 2020 (H2020) FET-OPEN project NARCISO (No. 828890), the French National Research Agency (ANR) through the projects ULYSSES (No. ANR-15-CE24-0027-01), OCTOPUS (No. ANR-18-CE47-0013-01), POINTCOM (No. ANR-23-CE24-0002-01), and the European Research Council (ERC) under the EU H2020 research and innovation program (Grant Agreement No. 724480). The authors thank the Nanotecmat platform of the IM2NP institute.

- [1] M. Khoury and M. Abbarchi, A bright future for silicon in quantum technologies, *J. Appl. Phys.* **131**, 200901 (2022).
- [2] M. S. Skolnick, A. G. Cullis, and H. Webber, Defect photoluminescence from pulsed-laser-annealed ion-implanted Si, *Appl. Phys. Lett.* **38**, 464 (1981).
- [3] K. Thonke, H. Klemisch, J. Weber, and R. Sauer, New model of the irradiation-induced 0.97-eV (G) line in silicon: A Cs-Si\* complex, *Phys. Rev. B* **24**, 5874 (1981).
- [4] A. N. Safonov, E. C. Lightowers, G. Davies, P. Leary, R. Jones, and S. Öberg, Interstitial-carbon hydrogen interaction in silicon, *Phys. Rev. Lett.* **77**, 4812 (1996).
- [5] L. Bergeron, C. Chartrand, A. T. K. Kurkjian, K. J. Morse, H. Riemann, N. V. Abrosimov, P. Becker, H.-J. Pohl, M. L. W. Thewalt, and S. Simmons, Silicon-integrated telecommunications photon-spin interface, *PRX Quantum* **1**, 020301 (2020).
- [6] A. Durand, Y. Baron, W. Redjem, T. Herzig, A. Benali, S. Pezzagna, J. Meijer, A. Y. Kuznetsov, J.-M. Gérard, *et al.*, Broad diversity of near-infrared single-photon emitters in silicon, *Phys. Rev. Lett.* **126**, 083602 (2021).
- [7] W. Redjem, A. J. Amsellem, F. I. Allen, G. Benndorf, J. Bin, S. Bulanov, E. Esarey, L. C. Feldman, J. F. Fernandez, J. G. Lopez, *et al.*, Defect engineering of silicon with ion pulses from laser acceleration, [arXiv:2203.13781](https://arxiv.org/abs/2203.13781) (2022).
- [8] M. Hollenbach, N. Klingner, N. S. Jagtap, L. Bischoff, C. Fowley, U. Kentsch, G. Hlawacek, A. Erbe, N. V. Abrosimov, M. Helm, *et al.*, Wafer-scale nanofabrication of telecom single-photon emitters in silicon, *Nat. Commun.* **13**, 7683 (2022).
- [9] V. Ivanov, J. Simoni, Y. Lee, W. Liu, K. Jhuria, W. Redjem, Y. Zhiyenbayev, C. Papapanos, W. Qarony, B. Kante, *et al.*, Effect of Localization on Photoluminescence and Zero-Field Splitting of Silicon Color Centers, *Phys. Rev. B* **106**, 134107 (2022).
- [10] W. Redjem, A. Durand, T. Herzig, A. Benali, S. Pezzagna, J. Meijer, A. Y. Kuznetsov, H. S. Nguyen, S. Cuéff, J.-M. Gérard, *et al.*, Single artificial atoms in silicon emitting at telecom wavelengths, *Nat. Electron.* **3**, 738 (2020).
- [11] G. Davies, E. C. Lightowers, and Z. E. Ciechanowska, The 1018 meV ( $W$  or  $I_1$ ) vibronic band in silicon, *J. Phys. C* **20**, 191 (1987).
- [12] S. Buckley, J. Chiles, A. N. McCaughan, G. Moody, K. L. Silverman, M. J. Stevens, R. P. Mirin, S. W. Nam, and J. M. Shainline, All-silicon light-emitting diodes waveguide-integrated with superconducting single-photon detectors, *Appl. Phys. Lett.* **111**, 141101 (2017).
- [13] G. Davies, E. C. Lightowers, and Z. E. Ciechanowska, The 1018 meV ( $w$  or  $i_1$ ) vibronic band in silicon, *J. Phys. C* **20**, 191 (1987).
- [14] A. Carvalho, R. Jones, J. Coutinho, and P. R. Briddon, Density-functional study of small interstitial clusters in Si: Comparison with experiments, *Phys. Rev. B* **72**, 155208 (2005).
- [15] S. M. Buckley, A. N. Tait, G. Moody, B. Primavera, S. Olson, J. Herman, K. L. Silverman, S. P. Rao, S. W. Nam, R. P. Mirin, *et al.*, Optimization of photoluminescence from W centers in silicon-on-insulator, *Opt. Express* **28**, 16057 (2020).
- [16] T. Menold, M. Ametowobla, and J. H. Werner, Signatures of self-interstitials in laser-melted and regrown silicon, *AIP Advances* **11**, 055212 (2021).
- [17] L. W. Song, X. D. Zhan, B. W. Benson, and G. D. Watkins, Bistable interstitial-carbon-substitutional-carbon pair in silicon, *Phys. Rev. B* **42**, 5765 (1990).
- [18] K. Murata, Y. Yasutake, K.-i. Nittoh, S. Fukatsu, and K. Miki, High-density G-centers, light-emitting point defects in silicon crystal, *AIP Advances* **1**, 032125 (2011).
- [19] D. D. Berhanuddin, M. A. Lourenço, R. M. Gwilliam, and K. P. Homewood, Co-Implantation of Carbon and Protons: An Integrated Silicon Device Technology Compatible Method to Generate the Lasing G-Center, *Adv. Func. Mater.* **22**, 2709 (2012).
- [20] H. Wang, A. Chroneos, C. A. Londos, E. N. Sgourou, and U. Schwingenschlögl, G-centers in irradiated silicon revisited: A screened hybrid density functional theory approach, *J. Appl. Phys.* **115**, 183509 (2014).
- [21] D. D. Berhanuddin, *Ph.d. thesis*, Surrey (2015).
- [22] C. Beaufils, W. Redjem, E. Rousseau, V. Jacques, A. Y. Kuznetsov, C. Raynaud, C. Voisin, A. Benali, T. Herzig, S. Pezzagna, *et al.*, Optical properties of an ensemble of g-centers in silicon, *Phys. Rev. B* **97**, 035303 (2018).
- [23] D. Timerkaeva, C. Attacalite, G. Brenet, D. Caliste, and P. Pochet, Structural, electronic, and optical properties of the C-C complex in bulk silicon from first principles, *J. Appl. Phys.* **123**, 161421 (2018).
- [24] C. Beaufils, *Ph.d. thesis*, Montpellier (2019).
- [25] W. Redjem, *Ph.d. thesis*, Université Montpellier (2019).
- [26] L. Zhu, S. Yuan, C. Zeng, and J. Xia, Manipulating Photoluminescence of Carbon G-center in Silicon Metasurface with Optical Bound States in the Continuum, *Adv. Opt. Mat.* **8**, 1901830 (2020).
- [27] M. Hollenbach, Y. Berencén, U. Kentsch, M. Helm, and G. V. Astakhov, Engineering telecom single-photon emitters in silicon for scalable quantum photonics, *Opt. Express* **28**, 26111 (2020).
- [28] P. Udvarhelyi, B. Somogyi, G. Thiering, and A. Gali, Identification of a telecom wavelength single photon emitter in silicon, *Phys. Rev. Lett.* **127**, 196402 (2021).
- [29] M. Hollenbach, N. S. Jagtap, C. Fowley, J. Baratech, V. Guardia-Arce, U. Kentsch, A. Eichler-Volf, N. V. Abrosimov, A. Erbe, C. Shin, *et al.*, Metal-assisted chemically etched silicon nanopillars hosting telecom photon emitters, *J. Appl. Phys.* **132**, 033101 (2022).
- [30] M. Khoury, H. Quard, T. Herzig, J. Meijer, S. Pezzagna, S. Cuéff, M. Abbarchi, H. S. Nguyen, N. Chauvin, and T. Wood, Light Emitting Si-Based Mie Resonators: Toward a Huygens Source of Quantum Emitters, *Adv. Opt. Mat.* **10**, 2201295 (2022).
- [31] M. Prabhu, C. Errando-Herranz, L. De Santis, I. Christen, C. Chen, and D. R. Englund, Individually Addressable Artificial Atoms in Silicon Photonics, [arXiv:2202.02342](https://arxiv.org/abs/2202.02342) (2022).
- [32] Y. Baron, A. Durand, T. Herzig, M. Khoury, S. Pezzagna, J. Meijer, I. Robert-Philip, M. Abbarchi, J.-M. Hartmann, S. Reboh, *et al.*, Single G centers in silicon fabricated by co-implantation with carbon and proton, *Appl. Phys. Lett.* **121**, 084003 (2022).



- [33] B. Lefaucher, J.-B. Jager, V. Calvo, A. Durand, Y. Baron, F. Cache, V. Jacques, I. Robert-Philip, G. Cassabois, T. Herzig, *et al.*, Cavity-enhanced zero-phonon emission from an ensemble of G centers in a silicon-on-insulator microring, *Appl. Phys. Lett.* **122**, 061109 (2023).
- [34] L. Komza, P. Samutpraphoot, M. Odeh, Y.-L. Tang, M. Mathew, J. Chang, H. Song, M.-K. Kim, Y. Xiong, G. Hautier, *et al.*, Indistinguishable photons from an artificial atom in silicon photonics, [arXiv:2211.09305](https://arxiv.org/abs/2211.09305) (2022).
- [35] Y. Zhiyenbayev, W. Redjem, V. Ivanov, W. Qarony, C. Papapanos, J. Simoni, W. Liu, K. Jhuria, L. Z. Tan, T. Schenkel, *et al.*, Scalable manufacturing of quantum light emitters in silicon under rapid thermal annealing, *Opt. Express* **31**, 8352 (2023).
- [36] Y. Baron, A. Durand, P. Udvarhelyi, T. Herzig, M. Khoury, S. Pezzagna, J. Meijer, I. Robert-Philip, M. Abbarchi, J.-M. Hartmann, *et al.*, Detection of single w-centers in silicon, *ACS Photonics* **9**, 2337 (2022).
- [37] D. D. Berhanuddin, M. A. Lourenço, R. M. Gwilliam, and K. P. Homewood, Co-implantation of carbon and protons: An integrated silicon device technology compatible method to generate the lasing g-center, *Adv. Func. Mater.* **22**, 2709 (2012).
- [38] T. Schenkel, W. Redjem, A. Persaud, W. Liu, P. A. Seidl, A. J. Amsellem, B. Kanté, and Q. Ji, Exploration of defect dynamics and color center qubit synthesis with pulsed ion beams, *Quantum Beam Sci.* **6** (2022).
- [39] J. Weber, Defect generation during plasma treatment of semiconductors, *Physica B* **170**, 201 (1991).
- [40] I. A. Buyanova, A. Henry, B. Monemar, J. L. Lindström, and G. S. Oehrlein, Photoluminescence of defects induced in silicon by sf6/o2 reactive-ion etching, *J. Appl. Phys.* **78**, 3348 (1995).
- [41] G. Andriani, G. Zanelli, S. D. Tchernij, E. Corte, E. N. Hernandez, A. Verna, M. Cocuzza, E. Bernardi, S. Virzì, P. Traina, *et al.*, Efficient activation of telecom emitters in silicon upon ns pulsed laser annealing, [arXiv:2304.10132](https://arxiv.org/abs/2304.10132) (2023).
- [42] K. Murata, Y. Yasutake, K. ichi Nittoh, K. Sakamoto, S. Fukatsu, and K. Miki, Hybrid laser activation of highly concentrated bi donors in wire- $\delta$ -doped silicon, *Appl. Phys. Express* **3**, 061302 (2010).
- [43] R. Monflier, T. Tabata, H. Rizk, J. Roul, K. Huet, F. Mazzamuto, P. Acosta Alba, S. Kerdilès, S. Boninelli, A. La Magna, *et al.*, Investigation of oxygen penetration during uv nanosecond laser annealing of silicon at high energy densities, *Appl. Surf. Sci.* **546**, 149071 (2021).
- [44] See Supplemental Materials for details of: i) comparison of the effect of the flash annealing on virgin and implanted samples, ii) global optical microscope view of the sample, iii) influence of the number of pulses on the ZPLs of G and W-centers, iv) micro-photoluminescence spectra and spatial distribution of the centers in the recrystallized area, v) removal of residual carbon on bulk Si.
- [45] J. Bonse, K. W. Brzezinka, and A. J. Meixner, Modifying single-crystalline silicon by femtosecond laser pulses: an analysis by micro Raman spectroscopy, scanning laser microscopy and atomic force microscopy, *Appl. Surf. Sci.* **221**, 215 (2004).
- [46] M. Garcia-Lechuga, N. Casquero, A. Wang, D. Grojo, and J. Siegel, Deep silicon amorphization induced by femtosecond laser pulses up to the mid-infrared, *Adv. Opt. Mat.* **9**, 2100400 (2021).
- [47] C. G. Kirkpatrick, J. R. Noonan, and B. G. Streetman, Recombination luminescence from ion implanted silicon, *Radiation Effects* **30**, 97 (1976).
- [48] J. R. Noonan, C. G. Kirkpatrick, and B. G. Streetman, Low-temperature photoluminescence from boron ion implanted silicon, *Radiation Effects* **21**, 225 (1974).
- [49] V. D. Tkachev, C. Schrödel, and A. V. Mudryi, Annealing of lattice damage in ion implanted silicon, *Radiation Effects* **49**, 133 (1980).
- [50] H. Feick and E. R. Weber, Annealing of the photoluminescence W-center in proton-irradiated silicon, *Physica B: Condensed Matter* **273-274**, 497 (1999).
- [51] G. Davies and K. T. Kun, Annealing the di-carbon radiation damage centre in silicon, *Semiconductor Science and Technology* **4**, 327 (1989).
- [52] R. Pässler, Basic Model Relations for Temperature Dependencies of Fundamental Energy Gaps in Semiconductors, *phys. stat. sol. (b)* **200**, 155 (1997).
- [53] M. Cardona and M. L. W. Thewalt, Isotope effects on the optical spectra of semiconductors, *Rev. Mod. Phys.* **77**, 1173 (2005).
- [54] S. Rudin, T. L. Reinecke, and B. Segall, Temperature-dependent exciton linewidths in semiconductors, *Phys. Rev. B* **42**, 11218 (1990).
- [55] P. Borri, W. Langbein, U. Woggon, M. Schwab, M. Bayer, S. Fafard, Z. Wasilewski, and P. Hawrylak, Exciton Dephasing in Quantum Dot Molecules, *Phys. Rev. Lett.* **91**, 267401 (2003).
- [56] Y.-C. Chen, P. S. Salter, M. Niethammer, M. Widmann, F. Kaiser, R. Nagy, N. Morioka, C. Babin, J. Erlekampf, P. Berwian, *et al.*, Laser writing of scalable single color centers in silicon carbide, *Nano Lett* **19**, 2377 (2019).
- [57] Y.-C. Chen, B. Griffiths, L. Weng, S. S. Nicley, S. N. Ishmael, Y. Lekhai, S. Johnson, C. J. Stephen, B. L. Green, G. W. Morley, *et al.*, Laser writing of individual nitrogen-vacancy defects in diamond with near-unity yield, *Optica* **6**, 662 (2019).
- [58] K. Jhuria, V. Ivanov, D. Polley, W. Liu, A. Persaud, Y. Zhiyenbayev, W. Redjem, W. Qarony, P. Parajuli, Q. Ji, *et al.*, Programmable quantum emitter formation in silicon (2023), [arXiv:2307.05759](https://arxiv.org/abs/2307.05759) [quant-ph].