Journal of Luminescence 133 (2013) 61–65

Contents lists available at SciVerse ScienceDirect

Journal of Luminescence

journal homepage: www.elsevier.com/locate/jlumin

Conversion efficiency of implanted ions by confocal micro-luminescence mapping

Y. Deshko [a], Mengbing Huang [b], A.A. Gorokhovsky [a,*]

[a] The College of Staten Island and The Graduate Center of CUNY, 2800 Victory Blvd., Staten Island, NY 10314, USA
[b] The University at Albany, The State University of New York, 1400 Washington Avenue, Albany, NY 12222, USA

ARTICLE INFO

Available online 6 November 2011

Keywords:
Ion implantation
Optical centers in diamond
Conversion efficiency
Confocal micro-luminescence mapping

ABSTRACT

We report on the further development of the statistical approach to determine the conversion efficiency of implanted ions into emitting centers and present the measurement method based on the confocal micro-luminescence mapping. It involves the micro-luminescence mapping with a narrow-open confocal aperture, followed by the statistical analysis of the photoluminescence signal from an ensemble of emitting centers. The confocal mapping method has two important advantages compared to the recently discussed aperture-free method (J. Lumin. 131 (2011) 489): it is less sensitive to errors in the laser spot size and has a well defined useful area. The confocal mapping has been applied to the Xe center in diamond. The conversion efficiency has been found to be about 0.28, which is in good agreement with the results of the aperture-free method.

1. Introduction

Ion implantation, followed by thermal annealing, is an established technique used to dope semiconducting materials and to create a number of optically active defects in solids. It furnishes a control over the spatial distribution, dose of implantation, and the type of the implanted ion. An optical defect is usually more complex than just a single implanted ion and often includes vacancies. Therefore not every implanted ion is converted into an optical center. The probability to form an optical center can be characterized by the conversion efficiency $q = N_{emit}/N_{impl}$, where N_{emit} and N_{impl} are the numbers of the emitting centers and the implanted ions filling a relevant "useful" volume, respectively. This parameter is important for single ion implantation for quantum optical and spin applications and for the use of defects as single center emitters [1,2]; however, it is difficult to estimate its value theoretically due to complex physico-chemical processes in the solids during ion implantation and annealing.

Determination of the conversion efficiency requires knowledge of both N_{emit} and N_{impl}. To measure N_{emit} one can either count single emitting centers directly or collect the optical signal S from ensembles of centers. The first approach requires a sophisticated single ion implantation setup and a sensitive single-emitter signal collection system with high spatial resolution. It has been successfully used for the generation of single N-V centers [3]. The second approach is simpler experimentally, but in this case one has to establish the relationship between the statistics of the emitting centers N_{emit} and the statistics of the collected signal S. Moreover, to find N_{impl} one has to know the implantation dose and the useful volume where the signal S is collected from.

In our previous work [4], we discussed the statistical approach and applied it to determine the conversion efficiency for Xe ions implanted into a high purity CVD diamond. This was done by analyzing a series of micro-luminescence maps. Two main factors were taken into account. Non-uniform illumination of the sample complicated the relationship between the collected signal S and the number of implanted ions N_{impl}. Secondly, the Gaussian profile of the laser beam and optical saturation led to the intensity-dependent size of the useful area R. Since the photoluminescence signal was collected by a confocal microscope with the aperture wide open (aperture-free method), the choice of the size of the useful area R was not obvious. Although the signal-to-noise criterion proposed in [4] gave reasonable results, it carried inherent uncertainty due to the random nature of the noise. In addition, to apply the aperture-free method one needs to measure the size of the focal spot w. The error of w contributed significantly to the uncertainty of the conversion efficiency (see Appendix). To avoid these difficulties, in this paper we discuss the further development of the statistical approach using micro-luminescence mapping involving a narrow-open confocal aperture. The aperture unambiguously sets the size of the useful area and makes the measurements less sensitive to the size of the focal spot w. Results obtained by both methods are compared.

* Corresponding author. Tel.: +1 718 982 2815; fax: +1 718 982 2830.
E-mail address: Anshel.Gorokhovsky@csi.cuny.edu (A.A. Gorokhovsky).

0022-2313/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jlumin.2011.10.033

2. Theoretical background

Since both the aperture-free and confocal mapping methods are based on the statistical approach they share some common theoretical aspects. To make the current work more self-contained, the main results of our previous paper [4] are briefly reviewed in Section 2.1. In order to decrease the experimental error in the conversion efficiency one has to measure the focal spot size with high precision. When this is difficult to achieve, the confocal mapping discussed in Section 2.2, can be used. In this method the size of the useful area is determined by the confocal aperture instead of the focal spot. In this manner it is possible to decrease the error. The downside of using the confocal aperture is the necessity to take the diffraction effects into account. The latter fact makes the analytical calculations of the correction factor β (see below) impossible and we use numerical Monte-Carlo simulation to estimate its value.

2.1. Aperture-free method

Consider an ensemble of optical centers randomly located in a thin planar layer close to the surface of the sample as shown in Fig. 1a. The total photoluminescence signal S, collected from the useful area of the sample, is given by the sum of the signals from the individual emitters: $S=\sum_{i=1}^{N} X_i$. The total number of emitters inside the useful area N_{emit} varies from point to point and is assumed to follow Poisson statistics with the property $\sigma_N^2=N_{emit}$. Under such assumptions the statistics of the random total signal S is compound Poisson with the following properties [5]: $\overline{S}=\overline{N}_{emit}\times\overline{X}$ and $\sigma_S^2=\overline{N}_{emit}\times\sigma_X^2+\overline{X}^2\times\sigma_N^2$. From these expressions one can find $\overline{N}_{emit}=\beta\times(\overline{S}^2/\sigma_S^2)$, where the factor $\beta\equiv\overline{X^2}/\overline{X}^2$ describes the difference between compound and regular ($\beta=1$) Poisson distributions. This factor has been calculated analytically for the case when a Gaussian laser beam $I(r)=I_0\times e^{-r^2/w^2}$ excites optical centers and the photoluminescence signal is then collected by a confocal microscope with the aperture wide open. The effects of optical saturation have also been taken into account. The calculations show that β is always greater than unity and situations when $\beta\gg 1$ are possible (Fig. 1b). The main point is that to estimate the factor β one needs to know the ratio of the size of the useful area to the size of the Gaussian laser beam $k=R/w$, as well as the level of optical saturation γ [4].

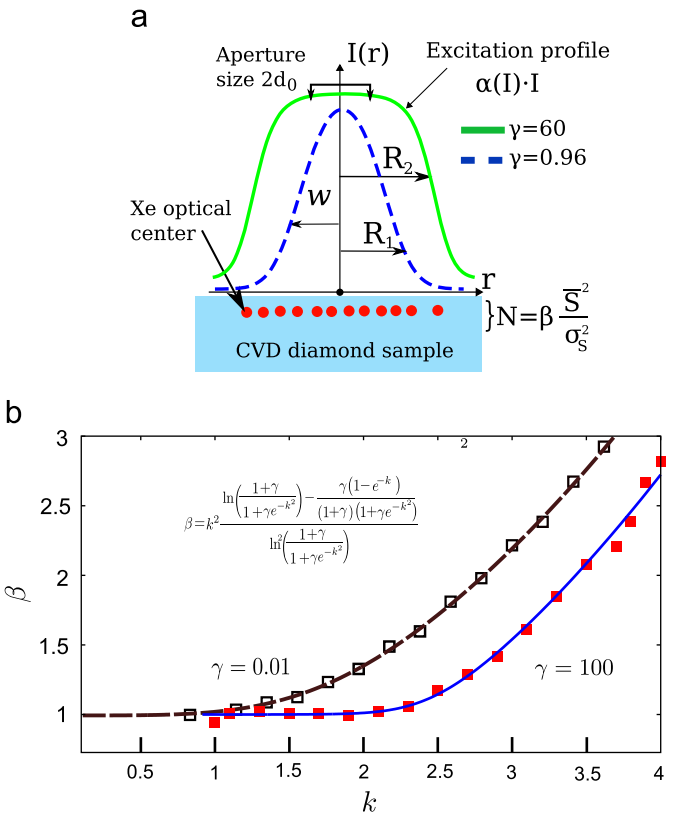

Fig. 1. (a) Excitation profiles in the focal spot. The Xe ions implanted into a CVD diamond sample form a thin 2D layer close to the surface. Optical centers are excited with a laser beam of a finite size w. The useful area from which the signal is collected has a radius $R>w$. The Gaussian illumination and the optical saturation each change the size of the useful area R (low and high levels of optical saturation are shown with R1 and R2, respectively); $\alpha(I)$ is the absorption coefficient. The signal S varies from point to point in accordance with a compound Poisson distribution and the average number of emitters N inside the useful area can be found. When the confocal aperture is present, the useful area is determined by the size of the aperture in the object plain do. It can be made smaller than R, in this case and the excitation is almost uniform. (b) The correction factor β as the function of $k=R/w$ — dimensionless size of the useful area; R is the useful area radius (in μm), w is the laser focal spot radius. In the aperture-free case the signal is collected from the useful area, which is greater than the focal spot, thus k must be greater than 1. Also, the factor β depends on the level of optical saturation. Two curves are shown, for low and high levels of optical saturation. As can be seen, the higher the optical saturation, the closer one gets to the simple case of a flat-top excitation, where $\beta=1$. The results of numerical simulations (explained in Section 2.2) are shown along with the calculated curves.

2.2. Confocal aperture method

The general expression for the correction factor is $\beta\equiv\overline{X^2}/\overline{X}^2$. The signal X from an individual optical center, positioned at a point r of the sample, is given by $X(r)=c\times I(r)\times\alpha(I)\times A(r)$. Here c is a constant that depends on the sensitivity of detection and on the quantum yield of the luminescence of the optical centers (assuming that all optical centers have equal yields of luminescence, the measured conversion efficiency q does not depend on the yield value!); $I(r)$ is the illumination profile; $\alpha(I)$ is the absorption coefficient; the factor $A(r)$ accounts for the effects of a confocal aperture. Because of the aperture and the diffraction only part of the signal X reaches the detector, therefore in general $A(r)<1$.

The confocal arrangement used is shown in Fig. 2a. The aperture should be smaller than the image of the focal spot: $d<M\times w$, where d is the aperture size, w is the focal spot size, and M is the magnification of the optical system. Together with the high level of optical saturation, this will make the excitation of the optical centers almost uniform everywhere in the useful area determined by the aperture as shown in Fig. 1a. This regime of measurements does not require the exact knowledge of the focal spot size w and is unaffected by the errors in w.

An optical center, being a point-like emitter, has an image of a finite size at the aperture (see Fig. 2b). This image defines a point spread function of the optical system with the characteristic size $\delta=0.6098\ \mathrm{M}\ \lambda/\mathrm{NA}$, here λ is the emission wavelength, and NA is the numerical aperture of the objective [6]. This increases the effective size of the useful area because some emitters projected outside of the aperture may still contribute part of their signal X to the total detected signal.

Unlike the aperture-free method, uniform flat-top excitation (i.e. $I(r)\times\alpha(I)=const$), does not lead to the Poisson statistics of the total signal. It means that the correction factor does not equal unity and is determined by the effects of the aperture and the diffraction: $\beta=\overline{A^2}/\overline{A}^2$. For a given shape and the size of the aperture and a particular form of the point spread function, the factor β can be calculated numerically. To this end one needs to simulate the experiment with a known number of emitters N ($N=1000$ was used in our simulations). In each trial, N points are randomly positioned inside a useful area of a certain size R. Summation of all signals from the individual emitters, with the effects of non-uniform excitation and the presence of aperture