JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. **6** No 3, 03018(3pp) (2014)

ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том **6** № 3, 03018(3cc) (2014)

On the Applicability of HF and μ-PCD Methods for Determination of Carrier Recombination Lifetime in the Non-passivated Single-crystal Silicon Samples

I.M. Anfimov, S.P. Kobeleva, I.V. Schemerov, M.N. Orlova

National University of Science and Technology "MISiS", 4, Leninsky Pr., 119049 Moscow, Russia

(Received 19 May 2014; published online 15 July 2014)

Comparison of the results of measuring the carrier recombination lifetime in silicon single crystals by contactless HF and microwave μ-PCD methods was carried out. It has been shown that HF method gives a large error compared with a μ-PCD method.

Keywords: Single-crystal silicon, Contactless μ-PCD method, Carrier recombination lifetime, Photoconductivity decay.

PACS number: 81.05.Dz

1. INTRODUCTION

The carrier recombination lifetime (τ_v) is the inverse value of recombination probability of a nonequilibrium electron (electron hole) in a unit of time. Shockley-Read-Hall recombination through deep centers dominates in the indirect-gap semiconductors such as silicon and germanium. Such metallic contaminations as iron or copper are typical deep recombination centers in Si and Ge. In silicon with resistivity (ρ) in the range from 1 to 1000 Ohm·cm τ_v is inversely proportional to the concentration of the recombination centers [1-7] and it can therefore be considered as the most important parameter of the quality of this semiconductor material. Recombination centers may significantly influence properties of the semiconductor devices, especially in the structures of submicrometer and nanometer sizes. So, with change of concentration of iron from 10^{12} cm^{-3} to 10^{9} cm^{-3} in the most pure silicon τ_v varies from a few microseconds to milliseconds, and it is easily detected, while there are no other available methods for the determination of such concentrations in industrial applications.

One of the main methods of determining τ_v is the measurement of the photoconductivity decay (PCD) [5-10]. More accurate method of determining τ_v is the contact PCD method [2, 3, 10], but it had not been used for industrial applications because of high labor consumption. More practically applicable variant of PCD method is the μ-PCD method owing to its nondestructive nature and high speed of measurement [8, 10, 11]. The decay curve in the μ-PCD method is strongly influenced by hardware factors and condition of the surface of a sample on which both volume and additional recombination take place. As a result the effective recombination time (τ_{eff}) which is measured depends on the ratio of three characteristic lengths — diffusion length (L_D), thickness of sample (d) (the size along the direction of the surface illumination), reciprocal light absorption factor and the surface recombination velocity (S) [2-8].

The equipment for the μ-PCD method demands calibration on referring samples (RS) with known effective time. The only μ-PCD method-capable RS manufactured in Russia was described in [12]. Samples were made of a high-resistance material with identical carrier recombination time. The certified value of τ_{eff} for RS was received by the HF measurement – a method in which the sample was placed between facings of a capacitor and signal attenuation in an RC circuit on kHz frequencies was measured. This method was chosen because there was a possibility of certifying the measuring system on measurement of a decay curve of standard capacities. In [12] it is noted that results of measuring RS by the μ-PCD equipment differ considerably from the certified data of a set. The purpose of this work is the analysis of the measurements of a RS package using HF and the μ-PCD methods and an assessment of application possibilities of HF as a method for RS certification.

2. SAMPLES AND EQUIPMENT FOR MEASUREMENT

The measurements have been carried out on the GIREDMET 48-0572-260(1-9)-2009 RS set. Samples of n-type silicon single-crystal were cut from a homogeneous ingot with the resistivity around 1.5 kOhm·cm. Various effective lifetimes have been obtained by using slices with different thicknesses. The non-passivated surface has been uniformly processed (polishing) which makes it possible to consider S within the range of 5000 to 15000 cm/s.

The calculations of τ_{eff} by the HF method were carried out by comparing the experimental curve and exponential decay curve with a known parameter on an oscilloscope screen. The standard error of the measurements is 10 %.

The measurements of τ_{eff} using the μ-PCD method were carried out on the automated μ-PCD detector APK-TAUMETR [13]. τ_{eff} were calculated using the portion of the decay signal in the range from 45-5 % of the peak signal according to recommendations [14-15]. Results of the measurements are presented in the Table 1. The statistical error of measurements does not exceed 8 %.

3. INTERPRETATION

For the analysis of the received results we used the equation for maximum τ_{eff} in the so-called infinite S approximation [2, 8, 11]:

The article was reported at the International Conference «The Advanced Technology, Equipment and Analytical Systems for Materials», Kursk, 13-14 May, 2014

Table 1 – RS data

Sample number	1	2	3	4	5	6	7	8
d, μm	9970	3140	2500	2000	1530	1070	760	315
Certified τ_{eff} measured by the HF method, μs	1590	470	300	170	106	73	45	17
τ_{eff} measured by the μ-PCD method, μs	1020	494	350	257	177	93,7	52,9	10,7

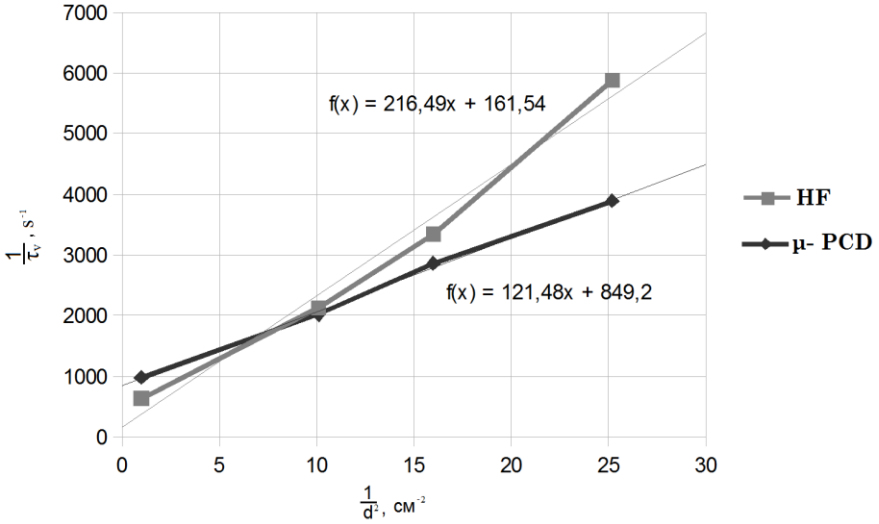

Fig. 1 – Correlation between τ_{eff} and thickness for samples 1-4

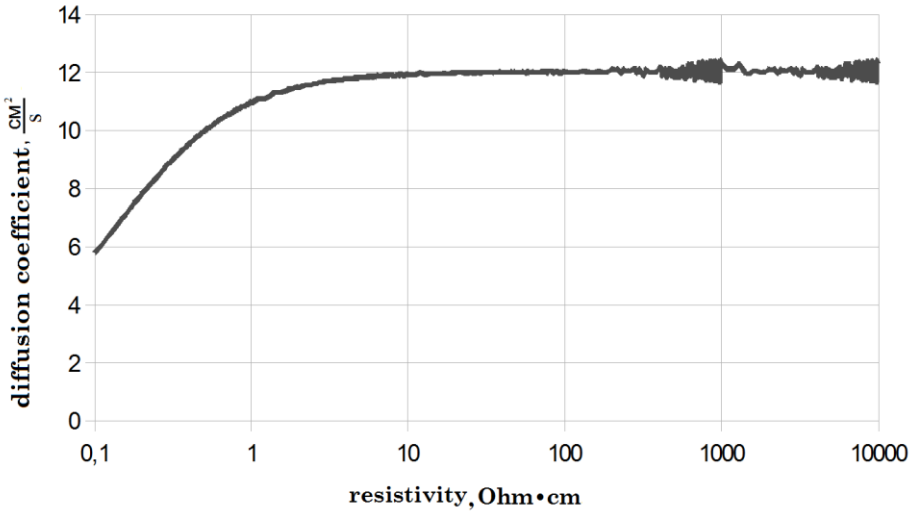

Fig. 2 – Correlation between the diffusion coefficient and the resistivity in single-crystal n-type silicon

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_v} + \frac{d^2}{\pi^2 D} \quad (1)$$

where D – diffusion coefficient, $m^2 \cdot s^{-1}$.

As it was shown in [11], equation (1) provides plausible values for thick samples with thickness exceeding diffusion length.

As we can see from data of Table 1, τ_v will exceed 1000 μs. This value corresponds to L_D of 1100 μm for an n-type Si. The L_D depends on the square root of τ_v, so a further increase of τ_v will lead to an insignificant L_D change. Therefore it is possible to assume that d for samples 1-4 exceeds the L_D value, and therefore (1) is applicable to samples 1-4. Fig. 1 illustrates a correlation between $1 / \tau_{eff}$ and $1 / d^2$ which, in accordance with (1), allows to determine τ_v and Dp. A high linearity and, as a result, a smaller error is observed for the μ-PCD method results. For the HF method $\tau_v = 3600 \pm 2000$ μs and $Dp = 19 \pm 3$ cm²/s, for the μ-PCD method $\tau_v = 1200 \pm 100$ μs and $Dp = 12 \pm 1$ cm²/s. Such τ_v values correspond to L_D of 2000 and 1190 μm respectively. Fig. 2 illustrates a correlation between Dp and resistivity from standard data [16]. In the samples with resistivity in the range 1-2 kOm·cm Dp changes from 11,5 to 12,5 cm²/s, thus Dp values calculated according to the μ-PCD measurements correspond rather closely to the

Table 2 – Comparison of τ_{eff}, obtained using equation (2) and measured using the μ-PCD and HF method

Sample number	1	2	3	4	5	6	7	8
τ_{eff} obtained from equation (2), μs	1020	494	372	270	178	96	53	10,8
Deviation from the μ-PCD measurements, %	0,0	0,0	6,3	4,9	0,7	2,5	0,1	1,1
Deviation from the HF measurements, %	– 35	5,1	24	58	68	32	17	– 36

standard data for Si single-crystal. This supports the reliability of the values obtained by μ-PCD method. At the same time the calculations using the HF measurements differ considerably from known published data. Equation (1) is not applicable for thin samples 5-8 [11], therefore calculations of τ_v should be performed on a more correct equation which takes into accountthe surface recombination velocity:

$$\frac{1}{\tau_v} = \frac{1}{\tau_{eff}} - \frac{1}{\tau_s}, \qquad \frac{1}{\tau_s} = \frac{d}{2S} + \frac{d^2}{\pi^2 D} \tag{2}$$

Usually (2) is not applied for calculations because S is unknown, and its measurement is a labor consuming task. For the results of this paper it is possible to determine S due to a large database including thin samples 5-8. Analysis of data obtained by the μ-PCD method showed that S is equal to 6700 cm/s ± 17 %.

S value for the HF method is not possible to determine using (2) because at the values of τ_v more than 1000 μs τ_s asymptotically tends to the τ_{eff} which would be less than the $d^2 / \pi^2 D$ value for samples 5-7.

We used S and τ_v values obtained to calculate the τ_{eff} using equation (2) for all samples. Results of calculations and their comparison with the μ-PCD measurements data are given in Table 2.

The calculations in Table 2 shows that the μ-PCD measurement results is more correct than the results of τ_{eff} measurements by HF method. The samples for this measurements is comparatively thick that allows to determine a correct volume lifetime.

It is known that more accurate results are obtained by contact measurements of photoconductivity decay based on the standard [14]. So for RS manufacturing it is necessary to use this method since the results of the contactless methods HF and μ-PCD differ dramatically.

4. CONCLUSIONS

The analysis of the measurement results of RS shows that the HF method can give a significant error as compared to the results of the μ-PCD method for thick samples (sample thickness more than L_D) and therefore cannot be used for the RS certification. For correct determination of volume lifetime and effective lifetime of referring samples contact measurements are necessary.

ACKNOWLEDGMENTS

The investigations were carried out on the equipment of the Common-Use Scientific Center "Materials Science and Metallurgy" of the NUST "MISIS" and with financial support from the Ministry of Education and Science of the Russian Federation in the framework of Increase Competitiveness Program of MISIS.

REFERENCES

1. D.K. Schroder, *Semiconductor Material and Device Characterization, 2-nd Ed.* (John Wileyand Sons: NewYork: 1998)
2. W.R. Runyan, T.J. Shaffner, *Semiconductor Measurements & Instrumentation* (McGraw-Hill: New York: 1997).
3. S.P. Kobeleva, *Zavodskaya Laboratroiya. Diagnostika Materialov* **73**, No 1, 60 (2007).
4. E. Gaubas, P. Clauws, et al., *Physica B* **401-402**, 222 (2007).
5. V.K. Khanna, *Prog. Quantum Electron.* **29**, 59 (2005).
6. B. Berger, N. Schuler, S. Anger, B. Grundig-Wendrock, J.R. Niklas, K. Dornich, *Contactless electrical defect characterization in semiconductors by microwave detected photo induced current transient spectroscopy(MD–PICTS) and microwave detected photoconductivity (MDP), 1* (BIAMS: Halle: 2010).
7. S. Dubois, O. Palaisa, P.J. Ribeyron, et al., *J. Appl. Phys.* **102**, 083525 (2007).
8. T. Pavelka, *Problems and Possibilities of comparing different Lifetime measuring instruments and techniques, 206* (Ed. by D.C. Gupta, W.M. Hughes, F.R. Bacher), (Recombination Lifetime Measurements in Silicon: ASTM International: 1998).
9. N. Schuler, S. Anger, K. Dornich, et al., *Sol. Energ. Mat. Sol. C.* **98**, 245 (2012).
10. S.P. Kobeleva, *Comments to Standards* No 8, 15 (2013).
11. I.M. Anfimov, S.P. Kobeleva, I.V. Schemerov, *Zavodskaya Laboratroiya. Diagnostika Materialov* **80** No 1, 41 (2014).
12. S.P. Kobeleva, P.B. Lagov, I.V. Schemerov, *Standard Samples* No 3, 10 (2013).
13. N.N. Goryunov, S.P. Kobeleva, I.A. Kalinin, *Zavodskaya Laboratoriya. Diagnostika Materialov* **70** No 6, 23 (2004).
14. SEMI MF28. *"Test Methods for the Minority-Carrier Lifetime in Bulk Germanium and Silicon by Measurement of Photoconductivity Decay".*
15. SEMI MF1535. *«Test method for carrier recombination lifetime in silicon wafers by non-contact measurement of photoconductivity decay by μ-PCD reflectance».*
16. SEMI MF723. *«Practice for conversion between resistivity and dopant or carrier density for boron-doped, phosphorus-doped, and arsenic-doped silicon».*