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Characterization of GaInP/Ge heterostructure solar cells by capacitance measurements at forward bias under illumination

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Abstract

The n-GaInP/n-p Ge heterostructure sloar cells grown by OMVPE were studied by new technique based on the diffusion capacitance measurements under illumination at open circuit voltage conditions. The value of the effective minority carrier lifetime in the p-Ge base τ_{eff}= 1.5×10^{-6} s was determined from the frequency dependence of the diffusion capacitance, *C*(*f*). The numerical simulation model was developed, which is in a good agreement with the experimental *C(f)*, capacitance-voltage and dark current-voltage measurements. The value of the bulk minority lifetime equal to τ_b= 5×10^{-6} s was obtained by the simulation fit of the experimental data. The simulations have also demonstrated that the diffusion capacitance is very sensitive to the recombination velocity at the back contact, S_{bc}, for S_{bc}<10^5 cm/s providing a way to characterize the back contact quality. Thus the proposed technique could be very useful for the back surface passivation development in GaInP/Ge solar cells.

Ge solar cells; lifetime measurements; capacitance measurements; surface recombination velocity

1. Introduction

In recent decades Ge becomes again to be of the great interest. For photovoltaic the Ge based structures are widely used in the thermo photovoltaic cells [1] and in very high efficient III-V multijunction solar cells [2]. The lattice constant of Ge is near to that of GaAs that provides a possibility of low dislocation density epitaxial growth of GaAs lattice matched III-V alloys on Ge wafers. Ge possesses a high mechanical strength and therefore the reduction of the thickness and weight of the Ge based photovoltaic structures is possible. The low band gap value (0.66 eV) of Ge allows one to use this material for a bottom subcell in multijunction solar cells extending the IR

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photosensitivity up to 1800 nm. A combination of the Ge, GaAs and GaInP subcells leads to the more than 40% efficiency of triple-junction solar cells [3]. While, there is a still room for improvement of Ge based subcells. For instance, in conventional design a metal ohmic contact is used at the back surface of the Ge cell. Recently, the new approach to back contact design using a back surface passivation by a-Si_xC_{1-x} thin films deposited by PECVD was suggested in [4]. The development of the back contact passivation requires the knowledge of the bulk life time of the minority carriers as well as a technique, which could be sensitive to the surface recombination velocity. The quality of the back surface may be estimated from the effective minority carrier lifetime, which in general case determined by the bulk and the surface carrier recombination.

One of the most used method for the effective minority carrier lifetime determination, which is widely used for the development of Si substrate passivation, is a quasi steady state photoconductance, QSSPC, method developed by R. Sinton [5]. But this technique can not be applied in case of the full metal back contact. Therefore the completed solar cells as well as substrates with back surface field contact formed by metal diffusion can not be characterized.

It was recently demonstrated for a-Si:H/c-Si heterojunction solar cells that the capacitance measured at forward bias close to open circuit voltage, V_{oc}, under AM1.5 illumination, being the diffusion capacitance, is sensitive to bulk material minority carriers lifetime as well as recombination rate at front and back interfaces [6]. The diffusion capacitance is determined by the excess minority carrier concentration and, therefore, is sensitive to the effective minority lifetime. Here this method based on diffusion capacitance measurements is proposed for characterization of GaInP/Ge heterostructure.

2. Experiment

Frequency dependence of the diffusion capacitance, $C(f)$, measurements were performed under illumination at direct bias equal to the open circuit voltage, V_{oc}. The illumination is necessary to avoid the measurement problem and influence, which are related to a high current level at direct bias. At open circuit voltage no current pass through the structure and, therefore, the perturbations of the measurement were minimized. The schematic presentation of the measurement setup is given in Fig.1. The capacitance was measured in the range of 100 Hz…1 MHz by E7-20 RCL-meter. The halogen 250 W lamp was used as a light source. The light flux was adjusted using mechanical diaphragm in order to keep the same applied voltage, V_a=V_{oc}=0.25 V, for the all structures. The exact value of the V_{oc} was measured by Keithley 2400 source-meter. The light intensity of the halogen lamp corresponded by the order of magnitude to one sun conditions for Ge solar cell (by short circuit current value). To avoid the heating of the cells during the capacitance measurements the sample temperature was controlled by Peltier effect cooler and was equal to 25ºC. The diffusion capacitance measurements were supplied by the dark current-voltage and capacitance-voltage measurements performed at room temperature using the mentioned above source- meters and RCL-meters, which were operated in four-terminal mode.

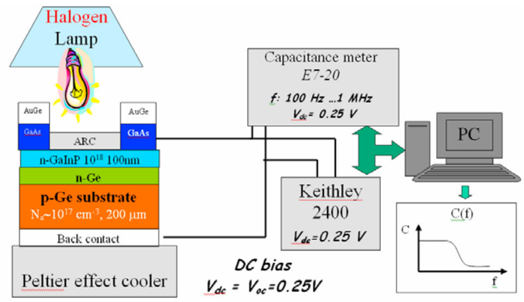

Fig.1. The schematic presentation of the diffusion capacitance measurement setup and GaInP/Ge solar cell structures.

The schematic view of the fabricated cells is also given in Fig.1. The n-GaInP/n-p-Ge heterostructures were fabricated by OMVPE growth of the n-GaInP layer on the p-Ge substrate. The growth conditions are in agreement with necessary conditions for perfect A^3B^5 crystal growth on Ge, described elsewhere [7]. The n-p junction in Ge was formed by the phosphorous diffusion from GaInP layer during the growth process. Phosphorous is a donor impurity in Ge. The values of the n-emitter layer depth and its doping density being equal approximately to 400 nm and 10^{18} cm^{-3}, respectively, were estimated by SIMS measurements. The substrate doping level was in the range of $N_a = 2\ldots8\times10^{17}$cm^{-3} and substrate thickness was 200 µm. The n-GaInP layer was caped by n+GaAs layer in order to form an ohmic metal contact grid at the top of the cell. The n+GaAs layer was etched by photolithography in order to form the photoactive area which was also coated by antireflection layers (ARC). The metal ohmic contact was formed at the back surface. The values of the n-emitter layer depth and its doping density being equal approximately to 400 nm and 10^{18} cm^{-3}, respectively, were estimated by SIMS measurements.

3. Results and discussions

The C(f) curves measured under illumination at open circuit voltage, V_{oc}=0.25 V, conditions for nine GaInP/Ge solar cells are presented in Fig.2. The samples were fabricated on the same wafer and by the same OMVPE process. The experimental curves of the all samples have the similar behaviour and the absolute values are in the range of the measurements accuracy. At low frequency the measurement accuracy decreases because the conductance contribution exceeds that of capacitance. Indeed, the admittance is equal to

$$Y(\omega) = G(\omega) + j\omega\cdot C(\omega) \qquad (1),$$

where $G(\omega)$ is the parallel conductance, ω - is an angular frequency and $C(\omega)$ is a parallel capacitance. At high frequency the imaginary part of the equation (1) is high enough compared to the real part and the capacitance could be measured relatively precisely. While at low frequency the real part, i.e. conductance, dominates over the imaginary part and the last can not be determined with the required accuracy for the capacitance measurements.

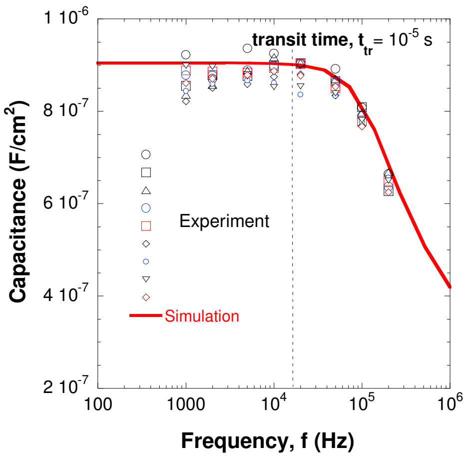

Fig.2. Experimental and simulated for τ_b= 5×10^{-6} s and N_a = 2.8×10^{17}cm^{-3} $C(f)$ curves under illumination at V_{oc}=0.25V.

However, the behaviour of the $C(f)$ curve at the high frequency region, where the diffusion capacitance drop is observed, is of the main interest. The frequency dependence of the diffusion admittance may be expressed as [8]:

$$Y_{diff}(\omega)= Y_0\,[1+j\omega\cdot t_{char}]^{1/2} \qquad (2),$$

where Y_0 is a frequency independent admittance prefactor and t_{char} is a characteristic time, which is equal to the effective lifetime of minority carrier, τ_{eff}, in case of a “long” diode and is equal to transit time, t_{tr}, in case of a “short” diode. The transit time is equal to [9]:

$$t_{tr} = W^2/2D_n \qquad (3),$$

where W is the base thickness, and D_n is a diffusion coefficient of the minority carriers. For the p-Ge substrates used for the solar cell fabrication the value of the transit time is approximately equal to 10^{-5} s. Using equation (2) we made a fit of the experimental C(f) curves and the value of the a characteristic time t_{char} =1.5×10^{-6} s was obtained. In this case $t_{char} << t_{tr}$ and, therefore, $t_{char} = \tau_{eff}$. This is an important issue, because it means that the effective lifetime value of the minority carrier in p-Ge base layer (substrate) can be determined from the frequency dependency of the diffusion capacitance.

For the further analysis the numerical simulations were involved. To improve the simulation model and to estimate the layer parameters the dark current-voltage, *I-V*, and capacitance-voltage, *C-V*, measurements performed at room temperature. The capacitance-voltage measurements demonstrated that $1/C^3 \propto V$ as can be seen from the linear dependence of $1/C^3(V)$ presented in Fig.3. This capacitance-voltage behavior was expected to be observed for the investigated n-p Ge junctions obtained by P diffusion. Because $1/C^3 \propto V$ dependences usual for a linearly graded p-n junctions [8] where capacitance may be expressed as:

$$C(V)=[(q\, a\, \varepsilon^2)/12(V_{bi}-V)]^{1/3} \qquad (4),$$

where q is a charge unit, ε is a dielectric permittivity, V_{bi} is a built-in potential and a is an impurity gradient, $a=|N_a - N_d|/d$, where N_a and N_d are the acceptor and donor doping density, respectively, d is a graded region thickness. From the experimental data (Fig.3) using equation (4) the impurity gradient was determined equal to a= 1.4×10^{22} cm^{-4}.

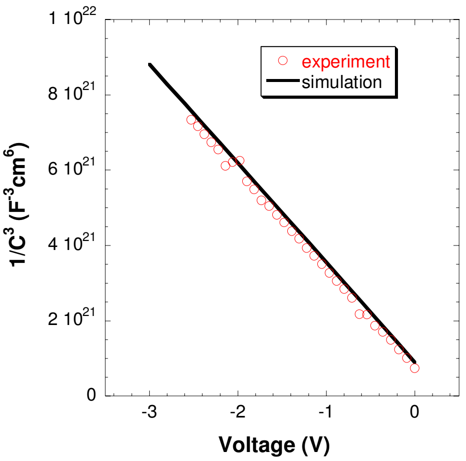

Fig.3. Experimental and simulated for τ_b= 5×10^{-6} s and N_a = 2.8×10^{17}cm^{-3} $1/C^3(V)$ curves.

The measured dark *I-V* curve is given in Fig. 4. The detailed analysis of the carrier transport based on temperature dependences of the dark *I-V* curves is given elsewhere [10]. The *I-V* curve consists of the diffusion current and tunneling current components. The former component dominates at the high current region. The last component being related to the recombination in the depletion region affects the *I-V* curves at the low current. We should stress that the diffusion current component is determined by $J_n \propto (\mu_n/\tau_n)^{1/2} \cdot n_{p0}$ relation for base and emitter layers, where μ, τ and n_{p0} are the mobility, lifetime and equilibrium concentration of the minority carriers. While the absolute value of the diffusion capacitance at low frequency is determined by $C_{LF} \propto (\mu_n \cdot \tau_n)^{1/2} \cdot n_{p0}$. The diffusion current and diffusion capacitance depends on τ and n_{p0} by different way. This is an important issue for the simulation. Because to simulate the both *I-V* and *C(f)* curves simultaneously the appropriate model and parameters should be used for the simulation.

The further analysis of a capability of the described technique for the GaInP/Ge solar cells characterization was made using numerical simulations. The simulations were performed using AFORS-HET 2.4.1 software [11], which allows one to simulate the graded layers. The surface recombination velocity for the electrons and holes were identical and varied in the range of S_{bc}=10^2…10^7 cm/s. A gradient layer with gradient value of a=1.4×10^{22} cm^{-4} and thickness of 400 nm was introduced between the emitter and base layers. The emitter thickness and doping level were taken equal to 400 nm and N_d = 10^{18}cm^{-3}, respectively, according to the SIMS measurements. The value of the minority carrier lifetime in the emitter was set equal to $\tau_e = 5\times10^{-9}$ s. The value of the bulk minority carrier lifetime in the base was varied in the range of $10^{-7}\ldots10^{-3}$ s.

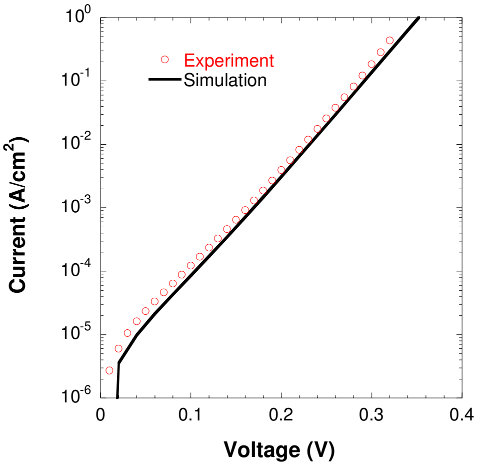

Fig.4. Experimental and simulated for $\tau_b = 5\times10^{-6}$ s and $N_a = 2.8\times10^{17}$cm^{-3} dark *I-V* curves.

First, the *C*(*f*) curves for the different values of the bulk minority carrier lifetime in the base, τ_b, and with $S_{bc}=10^7$ cm/s were simulated (Fig. 5). The increase of τ_b up to 5×10^{-5} s leads to the increase of the absolute diffusion capacitance value, C_{LF}, and to the shift of the *C*(*f*) curves toward lower frequency. Further increase of τ_b does not affect the *C*(*f*) curves. Because once τ_b becomes compatible with the transit time, t_{tr}, the effective minority carriers lifetime is limited by the surface recombination velocity ($S_{bc}=10^7$ cm/s) and only the t_{tr} value can be deduced from the frequency dependence. In Fig. 6 the *C*(*f*) curves simulated for the different values of S_{bc} with $\tau_b = 5\times10^{-6}$ s are presented. A decrease of S_{bc} from 10^7 to 10^5 cm/s almost does not change the *C*(*f*) curves. The recombination velocity is very high and all excess carriers recombine at the back surface (ohmic contact conditions).

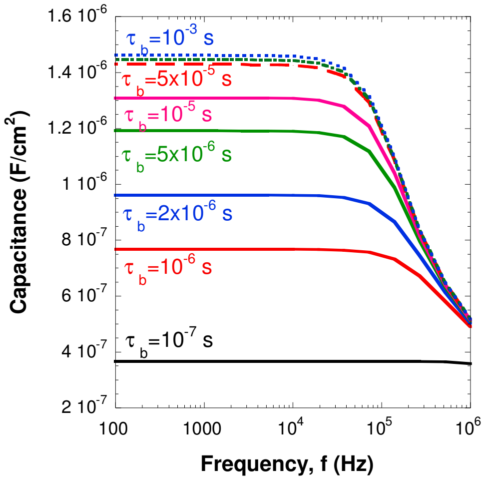

Fig. 5. Simulated *C(f)* curves under illumination at V_{oc}=0.25 V for different values of the bulk minority carrier lifetime, τ_b, and $S_{bc}=10^7$ cm/s.

While the decrease of the S_{bc} from 10^5 to 10^2 cm/s leads to the increase of the C_{LF} value and the curves shift toward lower frequency. The diffusion capacitance value is limited by the bulk minority lifetime value (τ_b= 5×10^{-6} s) and the further decrease of the S_{bc} does not lead to any changes in *C(f)*. The observed dependence of the diffusion capacitance, C_{LF}, value on S_{bc} may be used for the characterization of the back contact quality, for instance, for the development of the back surface passivation technology. This method has several advantages: i) the measurements may be performed with back metal contact; ii) C_{LF} is very sensitive to the recombination velocity at the back contact. Indeed, in Fig.7 the plot of the simulated values of the C_{LF} and V_{oc} under AM1.5D illumination versus S_{bc} is presented. The value of the C_{LF}, is much more sensitive to the recombination velocity at the back contact compared to the, V_{oc}, value.

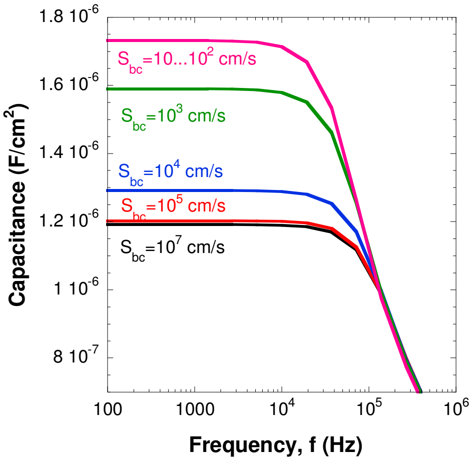

Fig. 6. Simulated *C(f)* curves under illumination at V_{oc}=0.25 V for different values of the surface recombination velocity, S_{bc}, and τ_b= 5×10^{-6} s.

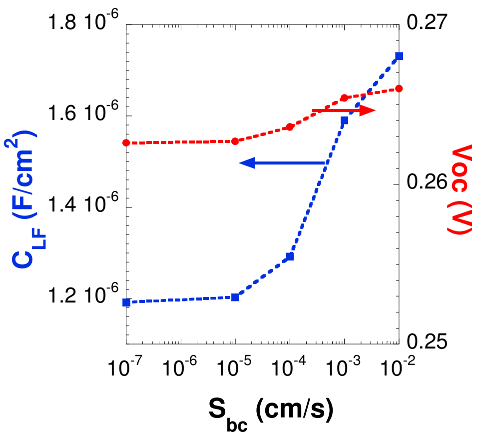

Fig.7. Calculated plots of C_{LF} at 0.25V and V_{oc} under AM1.5D illumination versus S_{bc}.

Finally, the experimental *C(f)*, *C-V* and dark *I-V* curves were simulated with a small variation of the parameters N_a, and τ_b. The fabricated GaInP/Ge heterostructures are assumed to have an ohmic back contact because no passivation was made. Therefore the value of S_{bc}=10^7 cm/s was used in the simulations. The simulated *C*(*f*), *C-V* and dark *I-V* curves for τ_b= 5×10^{-6} s and N_a = 2.8×10^{17}cm^{-3} are presented in Figs.2-4, respectively. All the simulated curves reproduce quite well the experimental data demonstrating that the model and parameters used in the simulations are in a coincident with experiment. We should stress that the obtained value of the minority carrier lifetime τ_b= 5×10^{-6} s is in a good agreement with the minority carrier diffusion length values obtained from spectral response in GaIn/Ge heterostructures prepared in the similar conditions [12].

4. Conclusions

The n-GaInP/n-p Ge heterostructure solar cells were characterized by the diffusion capacitance measurements under illumination at open circuit voltage, V_{oc}, conditions. It was demonstrated that the minority carrier transit time is longer compared to the effective minority carrier lifetime in the p-Ge base. Therefore, the latter may be determined from the frequency dependence of the diffusion capacitance. The value of the effective minority carrier lifetime equal 1.5×10^{-6} s was determined for the studied structures.

The numerical model of the Ge heterostructure solar cell was developed. The numerical simulations reproduce quite well the experimental *C*(*f*), dark *I*(*V*) and *C-V* curves, providing a set of appropriate parameters for the studied structures, like the bulk minority carrier lifetime in the base τ_b= 5×10^{-6} s, the impurity gradient a=1.4×10^{22} cm^{-4} and the accepter doping concentration N_a = 2.8×10^{17}cm^{-3} of the Ge substrate.

It was also shown by the simulations that the absolute value of the diffusion capacitance is sensitive more than value of V_{oc} under illumination to the recombination velocity at the back contact providing a way to characterize the back contact quality. Thus the proposed technique could be very useful for the chemical passivation or BSF development in GaInP/Ge solar cells.

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References

[1] V. M. Andreev, V. P. Khvostikov, N. A. Kalyuzhnyy, S. S. Titkov, O. A. Khvostikova and M. Z. Shvarts GaAs/Ge heterostructure photovoltaic cells fabricated by a combination of MOCVD and zinc diffusion techniques Semiconductors, Vol. 44, No. 8 (2010) pp. 355-359

[2] V.M.Andreev, GaAs and High-Eff iciency Space Cells, in: T. Markvart and L. Castafier (Eds.), Practical Handbook of Photovoltaics: Fundamentals and Applications, Elsevier Science, New York, 2003, pp. 417-433 .

[3] W. Guter, J. Schöne, S. P. Philipps, M. Steiner, G. Siefer, A. Wekkeli, E. Welser, E. Oliva, A. W. Bett and F. Dimroth, Current-matched triple-junction solar cell reaching 41.1% conversion efficiency under concentrated sunlight, Applied Physics Letters 94(22) (2009) 223504/1.

[4] J. Fernandez, S. Janz, D. Suwito, E. Oliva, F. Dimroth, Advanced concepts for high-efficiency germanium photovoltaic cells, Proc. of the 33rd IEEE Photovoltaic Specialists Conference (San Diego, 2008)

[5] R.A. Sinton, A. Cuevas, and M. Stuckings, "Quasi-Steady-State Photoconductance, A New Method for Solar Cell Material and Device Characterization," Proc of the 25th IEEE Photovoltaic Specialists Conference, pp. 457-460, 1996.

[6] A. S. Gudovskikh, J. P. Kleider, Capacitance spectroscopy of amorphous/crystalline silicon heterojunction solar cells at forward bias and under illumination. Appl. Phys. Letter 90 (2007) 034104.

[7] N.A. Kalyuzhnyy, V.M. Lantratov, S.A. Mintairov, M.A. Mintairov, M.Z. Shvarts, N.Kh. Timoshina and V.M. Andreev , “In-situ monitoring during mocvd growth of the triple-junction GaInP/Ga(In)As/Ge solar cells”, Proceedings of the 23th European Photovoltaic Solar Energy Conference, Valencia, Spain, 1-5 September, 2008, pp.803-810 (Session Code: 1DV.3.15

7+ N.A. Kalyuzhnyy, S.A. Mintairov, M.A. Mintairov & V.M. Lantratov, «Investigation of photovoltaic devices crystallization in mocvd with in-situ monitoring», Proceedings of the 24nd European Photovoltaic Solar Energy Conference, Hamburg, Germany, 21-25 September, 2009, pp.538-544.

[8] S. M. Sze (1981) *Physics of Semiconductor Devices*, 2nd Edition, John Wiley & Sons, New-York

[9] D.A. Neamen (2003), Semiconductor Physics and Devices: Basic Principles, 3rd Edition, MacGraw-Hill

[10] N.A. Kalyuzhnyy, A.S. Gudovskikh, V.V. Evstropov, V.M. Lantratov, S.A. Mintairov, N.Kh. Timoshina, M.Z. Shvarts, V.M. Andreev, Germanium subcells for multi-junction GaInP/GaInAs/Ge solar cells, Semiconductors Vol. 41 No 11 (2010)
[11] R.Stangl, M.Kriegel, M.Schmidt, Proc. WCPEC-4, 4th World Conference on Photovoltaic Energy Conversion, Hawaii, USA, May 2006.
[12] S. A. Mintairov, V. M. Andreev, V. M. Emelyanov, N. A. Kalyuzhnyy, N. K. Timoshina, M. Z. Shvarts, and V. M. Lantratov, Study of Minority Carrier Diffusion Lengths in Photoactive Layers of Multijunction Solar Cells, Semiconductors, Vol. 44, No. 8 (2010) pp. 1084–1089.