EAST EUROPEAN JOURNAL OF PHYSICS. **4.** 303-306 (2023)
DOI:10.26565/2312-4334-2023-4-39 ISSN 2312-4334

CAPACITIVE SPECTROSCOPY OF DEEP LEVELS IN SILICON WITH SAMARIUM IMPURITY

Sharifa B. Utamuradova*, Khojakbar S. Daliev, Shakhrukh Kh. Daliev, Uktam K. Erugliev
Institute of Semiconductor Physics and Microelectronics at the National University of Uzbekistan, Tashkent, Uzbekistan
**Corresponding Author e-mail: sh-utamuradova@yandex.ru*
Received October 1, 2023; revised October 24, 2023; accepted November 8, 2023

The effect of thermal treatment on the behavior of samarium atoms introduced into silicon during the growth process was studied using the method of transient capacitive deep-level spectroscopy (DLTS). It has been shown that various high-temperature treatments lead to the activation of samarium atoms in the bulk of n-Si and the formation of deep levels. The energy spectrum of deep levels arising during heat treatments has been determined. The dependence of the efficiency of formation of these levels in n-Si<Sm> on the processing temperature has been studied. It was found that the higher the content of samarium atoms in the bulk of silicon at the same high-temperature treatment temperature, the higher the concentration of the deep level E_C–0.39 eV. From this we can conclude that the EC–0.39 eV level is associated with the activation of samarium atoms in the n-Si<Sm> volume.
Keywords: *Capacitive spectroscopy; DLTS; Silicon; Doping; Samarium; Heat Treatment; Energy Spectrum; Deep Level; Formation Efficiency*
PACS: 71.20. – b, 71.28. + d

INTRODUCTION

It is known that the atoms of rare-earth elements introduced into the silicon lattice from the melt during growth, possessing high chemical activity and propensity to complexation, are present in silicon in an electrically inactive state [1-6]. The atoms of these rare earth elements in silicon can be activated by various external influences, such as heat treatment or irradiation [7-9].

In connection with the search for semiconductor materials with special properties (increased thermal stability, radiation resistance, etc.), interest in silicon doped with rare-earth elements has recently increased due to their essential role in the formation of silicon properties [10-12]. The world practice shows that during the technological processing of semiconductor wafers in the production of various structures and devices, various interactions of defects with each other occur, which are determined primarily by uncontrolled and specially introduced point defects characterized by maximum mobility in the lattice [13-16]. Therefore, the processes of defect structure formation of the crystal must be related to them.

In this work, the influence of various high-temperature treatments on the properties of silicon doped with samarium atoms during the growth process is investigated.

MATERIALS AND METHODS

Studies of the energy spectrum of deep levels (DL) appearing in samarium-doped silicon after various high-temperature treatments in the temperature range 900-1250 °C were carried out using the DLTS method on Schottky barriers created on the basis of initial and heat-treated samples of silicon with samarium impurity. The methods of measurement and processing of DLTS spectra, as well as the technology of Schottky barriers fabrication are described in [17-18].

The concentration of deep levels in n-Si<Sm> samples and control samples were determined from the maximum of DLTS peaks, as well as using volt-farad characteristics [18-21].

Measurements of DLTS spectra in the original n-Si<Sm> samples, (not subjected to high temperature treatments) showed that no deep levels were observed in appreciable concentration as well as in the original n-Si control samples. At the same time, additional studies by neutron activation analysis indicate the presence of Sm atoms in rather high concentrations (from 10^{15} to 10^{17} cm^{-3}) in the n-Si<Sm> volume.

These facts confirm the assumption of the authors [22,23] about electroneutrality of Sm atoms in Si. According to the same authors, the presence of Sm atoms has a noticeable effect on the thermal stability of Si.

In order to study the role of samarium in the processes of thermal defect formation in silicon and possible activation of samarium atoms under thermal effects, we carried out high-temperature treatments in the temperature range 900÷1200°C for 5÷10 h. Under the same conditions (T = 900÷1200°C, t = 5÷10 h) thermal annealing and control samples of n-Si (without samarium) were carried out in parallel.

RESULTS AND DISCUSSION

Fig. 1 shows DLTS spectra of n-Si<Sm> and n-Si samples heat-treated at 1200°C for 2 h followed by sharp quenching. The spectra were measured in constant voltage mode ($U_{samp.}$ =8 V) in the temperature range 77-300 K at t_1 = 10 ms and t_2 = 60 ms.

Cite as: Sh.B. Utamuradova, K.S. Daliev, Sh.Kh. Daliev, U.K. Erugliev, East Eur. J. Phys. 4, 303 (2023), https://doi.org/10.26565/2312-4334-2023-4-39

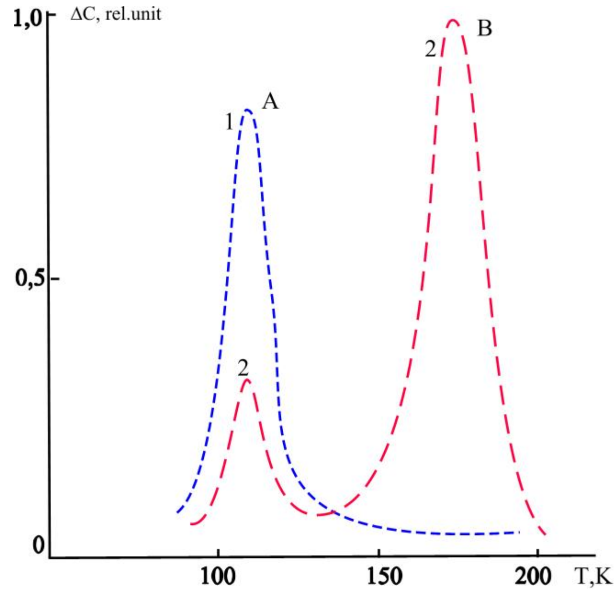

Figure 1. Typical DLTS spectra of n-Si control samples (curve 1) and n-Si<Sm> samples (curve 2) heat-treated at T = 1200°C

The dependences lg(θ) = f(10^3/T), the so-called Arrhenius plots [24], obtained from the DLTS spectra by comparing them with the calculated curve $\Delta C/\Delta C_{max}$ are shown in Fig. 2. These measurements showed that two peaks with maxima at T_{max} = 110 K (peak A) and T_{max} = 180 K (peak B) are observed in the DLTS spectra of silicon samples doped with samarium during growth and subjected to high-temperature treatment.

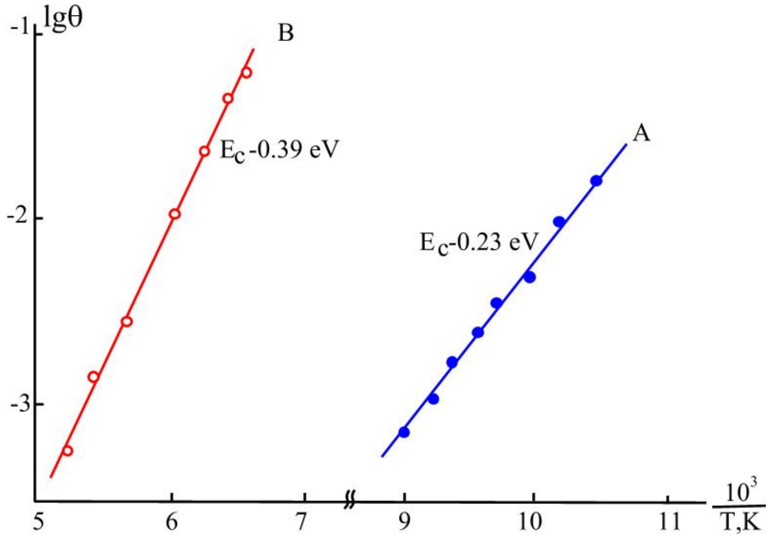

Figure 2. Temperature dependences of the recharge time constant of deep levels in n-Si<Sm> samples subjected to thermal treatment

From the slope of the dependences lg (θ)=f (10^3/T) for each of the DLTS peaks, it is obtained that the DLs occurring in the upper half of the forbidden zone of n-Si<Sm> samples (Fig.1, curve 2) as a result of high-temperature treatment have fixed ionization energies E_C-0.23 eV and E_C-0.39 eV and electron capture cross sections equal to $\sigma_n \sim 4\cdot10^{-17}$ and $1.2\cdot10^{-15}$ cm^2, and the concentrations of these levels after high-temperature treatment at T= 1200 °C are $3.9\cdot10^{13}$ cm^{-3} and $1.2\cdot10^{14}$ cm^{-3}, respectively.

The DLTS spectra of the heat-treated control samples of n-Si, which underwent the same heat treatment as n-Si<Sm>, show one deep level with ionization energy E_C-0.23 eV, electron capture cross section $\sigma_n \sim 4.10^{-17}$ and concentration $1.0\cdot10^{14}$cm^{-3} (Fig.1, curve 1).

Analysis of DLTS spectra shows that the concentrations of the observed levels in n-Si<Sm> samples strongly depend on the treatment temperature: the concentrations of DL E_C-0.23 eV and E_C-0.39 eV after high-temperature treatment at 1100°C (Fig.3, curve 1) have values of $5.7\cdot10^{13}$ cm^{-3} and $8.6\cdot10^{13}$ cm^{-3}, respectively, and after high-temperature treatment at 1200 °C (Fig.3, curve 2) their values are $3.9\cdot10^{13}$ cm^{-3} and $1.2\cdot10^{14}$ cm^{-3}, respectively.

In the heat-treated control n-Si samples, the concentration of E_C-0.23 eV level was $7.9\cdot10^{13}$ cm^{-3} (at T= 1100°C, Fig. 3, curve 3) and $1.0\cdot10^{14}$ cm^{-3} (at T= 1200 °C, Fig.3, curve 4).

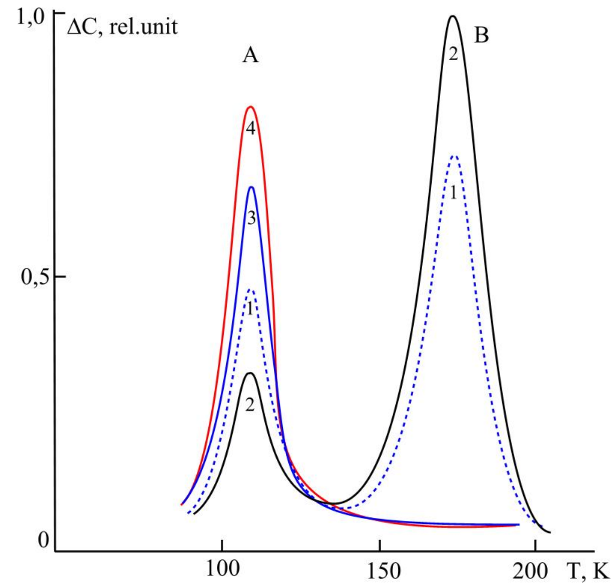

Figure 3. Typical DLTS spectra of heat-treated n-Si<Sm> (curves 1 and 2) and n-Si (curves 3 and 4) samples
T, °C: 1100 - curves 1 and 3, 1200 - curves 2 and 4

Comparison of the obtained results shows that the higher the temperature of high-temperature treatment, the greater the concentration of the deep level E_C-0.39 eV. On the contrary, the concentration of the level E_C-0.23 eV in n-Si<Sm>, which is also observed in the control samples, decreases markedly with increasing high-temperature treatment temperature. Note that at the same processing temperatures, the concentration of this deep level in the n-Si<Sm> samples, is much smaller than in the control n-Si samples (see Table 1).

In addition, it is found that the higher the content of samarium atoms in the silicon volume at the same temperature of high-temperature processing, the greater the concentration of the deep level E_C-0.39 eV. Hence, it can be concluded that the level E_C-0.39 eV is associated with the activation of samarium atoms in the n-Si<Sm> volume.

Table 1. Deep level concentrations of samples at different temperatures

Samples	T_{HTT}, °C	DL concentration, cm^{-3}	
		E_c- 0.23 eV	E_c- 0.39 eV
n-Si<Sm>	1100	$5.7\cdot10^{13}$	$8.6\cdot10^{13}$
n-Si<Sm>	1200	$3.9\cdot10^{13}$	$1.2\cdot10^{14}$
n-Si, control	1100	$7.9\cdot10^{13}$	--
n-Si, control	1200	$1.0\cdot10^{14}$	--

CONCLUSIONS

Thus, the analysis of the obtained results shows that samarium atoms introduced into the silicon lattice from the melt during the growth process are in the silicon volume in an electrically inactive state. High-temperature treatment in the range T = 900÷1200°C during t = 5÷10 h. leads to the formation of deep levels, probably associated with the activation of samarium atoms. The dependence of the efficiency of formation of deep levels E_C - 0.39 eV on the samarium content and processing temperature provides additional evidence that the observed deep levels are due to samarium atoms.

The level E_C - 0.23 eV is probably a defect of heat treatment, since it is observed in the control samples (heat treated without samarium).

It should be noted that the fact that the concentration of deep levels Es - 0.23 eV in samples of samarium-doped silicon is smaller than in control samples suggests that samarium atoms reduce the efficiency of formation of thermal defects in silicon.

ORCID
Sharifa B. Utamuradova, https://orcid.org/0000-0002-1718-1122; **Khojakbar S. Daliev**, https://orcid.org/0000-0002-2164-6797
Shakhrukh Kh. Daliev, https://orcid.org/0000-0001-7853-2777

REFERENCES

[1] O.V. Alexandrov, A.O. Zakhar'in, N.A. Sobolev, and Y.A. Nikolaev, Semiconductors, **36**(3), 379 (2002). https://doi.org/10.1134/1.1461417
[2] Kh.S. Daliev, Sh.B. Utamuradova, O.A. Bozorova, and Sh.Kh. Daliev, Applied Solar Energy, (**41**(1), 80 (2005). https://www.scopus.com/record/display.uri?eid=2-s2.0-33344466989&origin=resultslist&sort=plf-f
[3] X. Chuanyun, J. Blundell, F. Hagelberg, and A. William, International Journal of Quantum Chemistry, **96**(4), 416 (2004). https://doi.org/10.1002/qua.10735

[4] Kh.S. Daliev, Sh.B. Utamuradova, I.K. Khamidzhonov, A.Z. Akbarov, I.K. Mirzairova, and Z. Akimova, Inorganic Materials, **37**(5), 436 (2001). https://doi.org/10.1023/A:1017556212569
[5] Sh.B. Utamuradova, Kh.S. Daliev, E.K. Kalandarov, and Sh.Kh. Daliev, Technical Physics Letters, **32**(6), 469 (2006). https://doi.org/10.1134/S1063785006060034
[6] S.B. Utamuradova, and D.A. Rakhmanov, Annals of the University of Craiova, Physics, **32**, 132 (2022). https://cis01.central.ucv.ro/pauc/vol/2022_32/15_PAUC_2022_132_136.pdf
[7] S.Z. Zainabidinov, Kh.S. Daliev, K.P. Abdurakhmanov, Sh.B. Utamuradova, I.Kh. Khomidjonov, and I.A. Mirzamurodov, Modern Physics Letters B, **11**(20), 909 (1997). https://doi.org/10.1142/S0217984997001110
[8] R.L. Satet, M.J. Hoffmann, and R.M. Cannon, Materials Science and Engineering: A, **422**(1-2), 66 (2006). http://dx.doi.org/10.1016%2Fj.msea.2006.01.015
[9] C. Gross, G. Gaetano, T.N. Tucker, and J.A. Baker, Journal of the Electrochemical Society, **119**(7), 926 (1972). https://doi.org/10.1149/1.2404370
[10] S.I. Vlasov, D.E. Nazyrov, A.A. Iminov, and S.S. Khudaiberdiev, Technical Physics Letters, **26**(4), 328 (2000). https://doi.org/10.1134/1.1262833
[11] Sh.B. Utamuradova, Sh.Kh. Daliev, S.A. Muzafarova, and K.M. Fayzullaev. East European Journal of Physics, 3, 385 (2023). https://doi.org/10.26565/2312-4334-2023-3-41
[12] Sh.B. Utamuradova, Sh.Kh. Daliev, E.M. Naurzalieva, and X.Yu. Utemuratova, East European Journal of Physics, **3**, 430 (2023). https://doi.org/10.26565/2312-4334-2023-3-47
[13] N.A. Turgunov, E.Kh. Berkinov, and R.M. Turmanova, East European Journal of Physics, 3, 287 (2023). https://doi.org/10.26565/2312-4334-2023-3-26
[14] G. Gulyamov, S.B. Utamuradova, M.G. Dadamirzaev, N.A. Turgunov, M.K. Uktamova, K.M. Fayzullaev, A.I. Khudayberdiyeva, and A.I. Tursunov, East European Journal of Physics, 2, 221 (2023). https://doi.org/10.26565/2312-4334-2023-2-24
[15] Sh.B. Utamuradova, S.A. Muzafarova, A.M. Abdugafurov, K.M. Fayzullaev, E.M. Naurzalieva, and D.A. Rakhmanov, Applied Physics, **4**, 81(2021). https://doi.org/10.51368/1996-0948-2021-4-81-86
[16] X. Lan, J. Gao, K. Xue, H. Xu, and Z. Guo, Separation and Purification Technology, **293**, 121121 (2022). https://doi.org/10.1016/j.seppur.2022.121121
[17] K.P. Abdurakhmanov, Sh.B. Utamuradova, Kh.S. Daliev, S.G. Tadjy-Aglaeva, and R.M. Ergashev, Semiconductors, **32**(6), 606 (1998). https://doi.org/10.1134/1.1187448
[18] Sh.B. Utamuradova, Kh.I. Kalandarov, and J.J. Khamdamov, Semiconductor Physics and Microelectronics, **2**(2), 9 (2020). https://www.dropbox.com/s/7ykbddvwwiq3q8v/ON%20INTERACTION%20OF%20MANGANESE%20AND%20ZINC%20IMPURITIES%20IN%20SILICON.pdf?dl=0 (in Russian)
[19] Kh.S. Daliev, Natural and technical sciences, RAS, 2(40), 22 (2009). https://naukarus.com/vliyanie-primesi-gadoliniya-na-harakteristiki-kremnievyh-mdp-struktur (in Russian)
[20] L.S. Berman, and A.A. Lebedev, *Capacitance spectroscopy of deep centers in semiconductors*, Science, (Nauka, Leningrad, 1981). (in Russian)
[21] Kh.T. Igamberdyev, A.T. Mamadalimov, and P.K. Khabibullaev, Journal of Engineering Physics, **57**(4), 1220 (1989). https://doi.org/10.1007/BF00871143
[22] S. Zainabidinov, D.E. Nazyrov, and M.I. Bazarbaev, Electronic Materials Processing, **4**, 90 (2006). https://cyberleninka.ru/article/n/diffuziya-rastvorimost-i-elektricheskie-svoystva-samariya-i-itterbiya-v-kremnii/pdf (in Russain)
[23] K.H. Goh, A.S. Haseeb, and Y.H. Wong, Journal of Alloys and Compounds, **722**, 729 (2017). https://doi.org/10.1016/j.jallcom.2017.06.179
[24] D.V. Lang, Journal of Applied Physics, **45**, 3023 (1974). http://dx.doi.org/10.1063/1.1663719

ЄМНІСНА СПЕКТРОСКОПІЯ ГЛИБОКИХ РІВНІВ У КРЕМНІЇ З ДОМІШКОЮ САМАРІЮ †

Шаріфа Б. Утамурадова, Ходжакбар С. Далієв, Шахрух Х. Далієв, Уктам К. Єруглієв
Інститут фізики напівпровідників і мікроелектроніки Національного університету Узбекистану, Ташкент, Узбекистан

Методом перехідної ємнісної глибокорівневої спектроскопії (DLTS) досліджено вплив термічної обробки на поведінку атомів самарію, введених у кремній у процесі росту. Показано, що різні високотемпературні обробки призводять до активації атомів самарію в об'ємі n-Si та утворення глибоких рівнів. Визначено енергетичний спектр глибоких рівнів, що виникають під час термічних обробок. Досліджено залежність ефективності утворення цих рівнів в n-Si<Sm> від температури обробки. Виявлено, що чим вищий вміст атомів самарію в об'ємі кремнію при однаковій температурі високотемпературної обробки, тим вища концентрація глибокого рівня EC-0,39 еВ. З цього можна зробити висновок, що рівень EC-0,39 еВ пов'язаний з активацією атомів самарію в об'ємі n-Si<Sm>.

Ключові слова: *ємнісна спектроскопія; DLTS; кремній; легування; самарій; термообробка; енергетичний спектр; глибокий рівень; ефективність формування*