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Volume: 92
Number: 19
Page Range: 192114
Year: 2008

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URL: http://hdl.handle.net/2241/99941

doi: 10.1063/1.2929744
Lifetime and diffusion length of photogenerated minority carriers in single-crystalline \textit{n}-type \textit{\beta}-FeSi\textsubscript{2} bulk

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(Received 21 March 2008; accepted 15 April 2008; published online 15 May 2008)

We have evaluated the lifetime and diffusion length of photogenerated minority carriers (holes) in single-crystalline \textit{n}-type \textit{\beta}-FeSi\textsubscript{2} bulk grown by chemical vapor transport. The diffusion length measured by optical-beam-induced current agreed well with that measured by electron-beam-induced current, that is, 51 and 38 $\mu$m, respectively, for samples annealed at 800 °C for 8 h. The decay curve of photoc conductivity obtained by 1.31 and 1.55 $\mu$m light pulses was well fitted by assuming a carrier lifetime of approximately a few microseconds. The mobility of photogenerated minority carriers was estimated to be approximately 200–360 cm$^2$/V s from the measured lifetime and diffusion length. © 2008 American Institute of Physics.

[DOI: 10.1063/1.2929744]

Semiconducting \textit{\beta}-FeSi\textsubscript{2} has been attracting a great deal of attention as a Si-based light emitter and photodetector operating at wavelengths suitable for optical fiber communications (1.3–1.5 $\mu$m). This is because \textit{\beta}-FeSi\textsubscript{2} has a band gap of approximately 0.78 eV,\textsuperscript{1} and a very large optical absorption coefficient of over 10\textsuperscript{5} cm$^{-1}$ at 1 eV.\textsuperscript{2} Recent reports on \textit{\beta}-FeSi\textsubscript{2} light-emitting diodes operating at room temperature (RT) have served to further increase interest in this material.\textsuperscript{3–6} In contrast, there have been a limited number of reports discussing the photoresponsivity of \textit{\beta}-FeSi\textsubscript{2}. The highest photoresponsivity ever reported is 0.1 mA/W at 1.60 $\mu$m.\textsuperscript{9} In our previous papers, we have fabricated an \textit{Al/n-\beta}-FeSi\textsubscript{2} Schottky diode structure using \textit{\beta}-FeSi\textsubscript{2} single crystals grown by chemical vapor transport (CVT) in place of \textit{\beta}-FeSi\textsubscript{2} films on Si substrates.\textsuperscript{11,12} We have chosen \textit{\beta}-FeSi\textsubscript{2} single crystals to avoid the influence of grain boundaries on \textit{\beta}-FeSi\textsubscript{2} films and Fe-related deep levels on Si in the case of \textit{\beta}-FeSi\textsubscript{2}/Si. The photoresponsivity reached 58 mA/W upon annealing at 800 °C for 8 h.\textsuperscript{11} This value is more than two orders of magnitude larger than the highest value ever reported. The electron-beam-induced current (EBIC) measurements revealed that the enhanced diffusion length was attributed to an unexpectedly large minority-carrier diffusion length. The diffusion length was estimated to be 20 $\mu$m, and increased up to approximately 30 $\mu$m after annealing at 800 °C for 8 h.\textsuperscript{12} However, our previous paper has been the only one thus far reporting the diffusion length in \textit{\beta}-FeSi\textsubscript{2}.\textsuperscript{12} Therefore, it is very important to verify the diffusion length by utilizing alternative methods. In this letter, we have evaluated the photogenerated minority-carrier diffusion length in \textit{n}-type \textit{\beta}-FeSi\textsubscript{2} single crystals by optical-beam-induced current (OBIC) technique using an \textit{Al/n-\beta}-FeSi\textsubscript{2} Schottky diode and compare that with those obtained by EBIC. A good agreement was obtained between them. The minority-carrier lifetime was also measured by photoc conductivity decay measurements.

Two kinds of \textit{n}-type \textit{\beta}-FeSi\textsubscript{2} single crystals with different starting materials were prepared by CVT,\textsuperscript{13} as summarized in Table I. Subsequent process is same as a previous paper.\textsuperscript{12} The EBIC observation was done in the edge-scan configuration with a Hitachi S4200 field-emission scanning electron microscope in EBIC mode at RT.\textsuperscript{14} The acceleration voltage of electron beam was 20 kV. The OBIC profiles were obtained using Olympus STM-6 measurement optical microscope with microscopic Raman measurement optics. The excitation light was given by a continuous-wave 1.31 $\mu$m single-mode laser diode (SM-LD) light and an Ar-Kr gas laser emitting at 752 nm. Another emission peaking at 647 nm was included a little in the Ar-Kr laser. The carrier lifetime was measured at RT from photoc conductivity decay measurements excited by a 1.31 or 1.55 $\mu$m laser pulse given by SM-LD.

Figures 1(a) and 1(b) show secondary-electron- and EBIC images around the Al contact, respectively, measured on the annealed AP63. The semilogarithmic plot of EBIC line-scan data along the dotted line and fitting are shown in Fig. 1(c). The EBIC profile shows a clear exponential dependence of distance from the Al contact. The diffusion length was roughly estimated to be 38 $\mu$m, assuming that the EBIC profile varies as $\exp(-x/L)$, where $x$ is the distance from the

<table>
<thead>
<tr>
<th>Sample</th>
<th>Starting materials</th>
<th>Annealing</th>
<th>Wavelength</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP63</td>
<td>Fe(4N8): Si(5N) = 1.6:2.0</td>
<td>no</td>
<td>1.31 $\mu$m</td>
<td>not detected</td>
</tr>
<tr>
<td></td>
<td></td>
<td>800 °C/8 h</td>
<td>1.31 $\mu$m</td>
<td>2.7 $\mu$s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>800 °C/8 h</td>
<td>1.55 $\mu$m</td>
<td>3.1 $\mu$s</td>
</tr>
<tr>
<td>AP64</td>
<td>Fe(4N8): Si(5N) = 1.4:2.0</td>
<td>no</td>
<td>1.31 $\mu$m</td>
<td>0.17 $\mu$s</td>
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<tr>
<td></td>
<td></td>
<td>800 °C/8 h</td>
<td>1.31 $\mu$m</td>
<td>1.1 $\mu$s</td>
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<tr>
<td></td>
<td></td>
<td>800 °C/8 h</td>
<td>1.55 $\mu$m</td>
<td>1.1 $\mu$s</td>
</tr>
</tbody>
</table>

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Al edge and \( L \) is the diffusion length of holes.

Figure 2 shows the OBIC profile of the same sample. The OBIC line-scan data along the broken line in Fig. 2(a) is plotted in Figs. 2(b) and 2(c). The OBIC profiles on both sides of the Al contact show the same exponential dependence of distance as the EBIC profile shown in Fig. 1. The diffusion length was estimated to be approximately 50 \( \mu \)m for a 33 \( \mu \)m diameter 1.31 \( \mu \)m light, as shown in Fig. 2(c). Almost the same diffusion length was obtained for an 11 \( \mu \)m diameter 752 nm light. The origin of a small difference in diffusion length between EBIC and OBIC measurements has not been made clear. However, we speculate that it is attributed to a large difference in excitation energy between them. We should also note that the photoresponsivity reached 87 mA/W, the highest value ever reported, as shown in Fig. 2(b). Furthermore, the photoresponsivity is expected to reach the maximum of approximately 0.2 A/W at \( x = 0 \), provided that the Al contact does not disturb the light illumination on the \( \beta \)-FeSi\(_2\) surface. On the basis of these results, we conclude that the diffusion length obtained by EBIC was reproducible by OBIC, and also that \( \beta \)-FeSi\(_2\) is very promising as a material for detectors even at the present stage.

Next, we evaluate the lifetime of photogenerated minority carriers (holes) in \( n \)-\( \beta \)-FeSi\(_2\) and discuss the mobility of holes. The diffusion length \( L \) is related to carrier lifetime \( \tau \) and diffusion length \( L \) by the following expressions as \( L = (D\tau)^{1/2} \) and \( D = \mu kT/q \), where \( \mu \) is the hole mobility, \( k \) is the Boltzmann constant, \( T \) is the absolute temperature, and \( q \) is the elementary charge. Figure 3 shows the decay curve in photoconductivity measured on the annealed \( \beta \)-FeSi\(_2\) single crystal (AP63) using a 1.31 \( \mu \)m light pulse. Semilogarithmic plot of the decay curve was shown in Fig. 3(b). The decay curve was well fitted assuming that it is composed of the sum of three exponentials, with the decay time of approximately 0.1, 0.7, and 2.7 \( \mu \)s. The fast two components changed depending on the place where the light pulses were illuminated on the sample, and became small or even disappeared for a light pulse with longer wavelength \( \lambda = 1.55 \) \( \mu \)m. In contrast, the longer decay time of approximately 2.7 \( \mu \)s remained unchanged. At larger photon energies (\( \lambda = 1.31 \) \( \mu \)m), the penetration depth becomes shorter. Thus, we think that the long decay time is specific to the sample, and that the fast decay components were influenced by surface recombination. For this reason, we chose a longer decay time as a lifetime hereafter. Table 1 summarizes lifetimes obtained for various samples. We can say that the carrier lifetime increased by the high-temperature annealing in both samples AP63 and AP64 and it amounts to approximately a few microseconds. It was also found that the lifetime deviated a little, depending on a ratio of Fe to Si (Fe/Si ratio), in the initial growth stage of CVT. However, this is not the main subject of this paper. The influence of Fe/Si ratio on carrier lifetime and photoresponsivity will be discussed elsewhere.

Now that the diffusion length and carrier lifetime in \( n \)-type \( \beta \)-FeSi\(_2\) were obtained, we are able to calculate the hole mobility. When we use the diffusion length of 38 (EBIC) and 51 \( \mu \)m (OBIC), and the carrier lifetime of 2.7 \( \mu \)s, the hole mobility is calculated to be approximately 200 and 360 cm\(^2\)/V s, respectively. These values are almost the same as those reported in high-quality \( \beta \)-FeSi\(_2\) epitaxial films.\(^{15,16}\) These large mobilities of hole can be well explained by means of classical scattering mechanisms, namely, by the acoustic and nonpolar phonon modes as well as by the charged and neutral impurity scatterings.\(^{17,18}\) However, the hole mobility in \( p \)-type \( \beta \)-FeSi\(_2\) bulk has been reported to be in the range of 10–20 cm\(^2\)/V s.\(^{19,21}\) We think...
The photogenerated minority carriers in further discussion is necessary.

Light pulse. The measurement circuit was inserted. The formation on the electrical properties of measurement errors. However, we have only limited in-
that the Hall measurements might contain a certain amount of photoconductivity with time and fitting using three decay times.

In conclusion, we have investigated the $L$ and $\tau$ values of photogenerated minority carriers in $n$-type $\beta$-FeSi$_2$ crystals. The $\tau$ value increased up to a few microseconds at RT upon annealing at 800 °C for 8 h. The $L$ value measured by EBIC agreed well with that by OBIC. They were approximately 38 and 51 $\mu$m, respectively. The hole mobility was calculated to be in the range of 200–360 cm$^2$/V s at RT.

We would like to thank Dr. Y. Makita, Mr. Y. Nakayama, and Mr. Y. Fukuzawa of KANKYO-semiconductors Co., Ltd. for their collaboration in this work.


