Lifetime and diffusion length of photogenerated minority carriers in single-crystalline *n*-type β-$FeSi_2$ bulk

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We have evaluated the lifetime and diffusion length of photogenerated minority carriers (holes) in single-crystalline *n*-type β-$FeSi_2$ 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 μm, respectively, for samples annealed at 800 °C for 8 h. The decay curve of photoconductivity obtained by 1.31 and 1.55 μm 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*.
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Semiconducting β-$FeSi_2$ 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 μm). This is because β-$FeSi_2$ has a band gap of approximately 0.78 eV,[1] and a very large optical absorption coefficient of over $10^5\ cm^{-1}$ at 1 eV.[2] Recent reports on β-$FeSi_2$ light-emitting diodes operating at room temperature (RT) have served to further increase interest in this material.[3–6] In contrast, there have been a limited number of reports on photodetectors using β-$FeSi_2$.[7–10] In particular, there have been only a few reports discussing the photoresponsivity of β-$FeSi_2$. The highest photoresponsivity ever reported is 0.1 mA/W at 1.60 μm.[9] In our previous papers, we have fabricated an Al/*n*-β-$FeSi_2$ Schottky diode structure using β-$FeSi_2$ single crystals grown by chemical vapor transport (CVT) in place of β-$FeSi_2$ films on Si substrates.[11,12] We have chosen β-$FeSi_2$ single crystals to avoid the influence of grain boundaries on β-$FeSi_2$ films and Fe-related deep levels on Si in the case of β-$FeSi_2$/Si. The photoresponsivity reached 58 mA/W upon annealing at 800 °C for 8 h.[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 μm, and increased up to approximately 30 μm after annealing at 800 °C for 8 h.[12] However, our previous paper has been the only one thus far reporting the diffusion length in β-$FeSi_2$.[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 *n*-type β-$FeSi_2$ single crystals by optical-beam-induced current (OBIC) technique using an Al/*n*-β-$FeSi_2$ 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 photoconductivity decay measurements.

Two kinds of *n*-type β-$FeSi_2$ single crystals with different starting materials were prepared by CVT,[13] as summarized in Table I. Subsequent process is same as a previous paper.[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.[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 μm 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 photoconductivity decay measurements excited by a 1.31 or 1.55 μm 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 μm, assuming that the EBIC profile varies as $\exp(-x/L)$, where x is the distance from the

TABLE I. Starting materials of CVT, annealing condition, wavelength of light in carrier lifetime measurement and deduced carrier lifetime.

Sample	Starting materials	Annealing	Wavelength	Lifetime
AP63	Fe(4*N*8):Si(5*N*)=1.6:2.0	no	1.31 μm	not detected
		800 °C/8 h	1.31 μm	2.7 μs
		800 °C/8 h	1.55 μm	3.1 μs
AP64	Fe(4*N*8):Si(5*N*)=1.4:2.0	no	1.31 μm	0.17 μs
		800 °C/8 h	1.31 μm	1.1 μs
		800 °C/8 h	1.55 μm	1.1 μs

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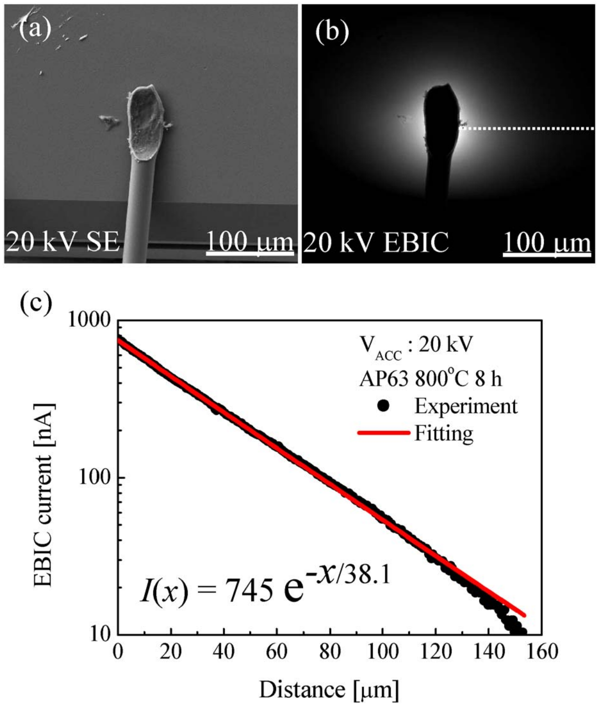

FIG. 1. (Color online) (a) SE image and (b) EBIC image around the Al contact measured on sample AP63. (c) Semilogarithmic plot of EBIC line-scan data along the dotted line and fitting to the experimental data.

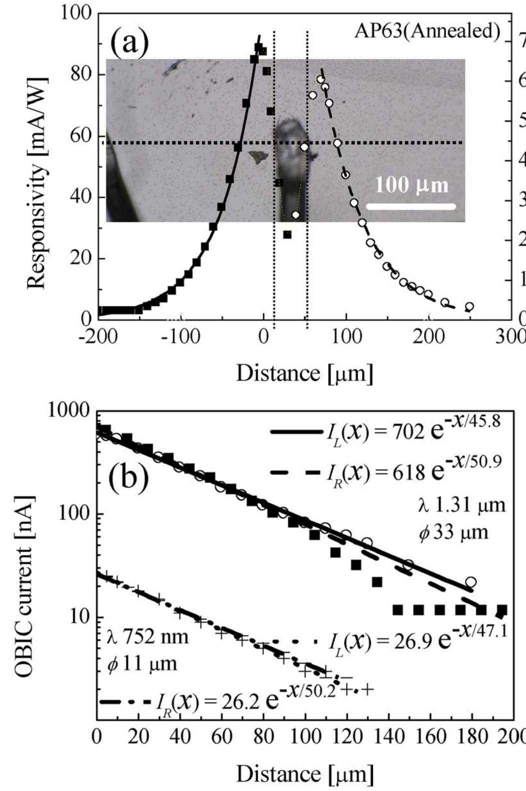

FIG. 2. (Color online) (a) OBIC line-scan data along the broken line of inserted optical microscope image on both sides (■, ○) of the Al contact and photoresponsivity using a 1.31 μm light. (b) Semilogarithmic plots of OBIC line-scan data obtained using a 1.31 μm light (■, ○) and a 752 nm light (+, −).

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 μm for a 33 μm diameter 1.31 μm light, as shown in Fig. 2(c). Almost the same diffusion length was obtained for an 11 μm diameter 752 nm light. The origin of a small difference in diffusion length between EBIC and OIBC 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 value of approximately 0.2 A/W at $x=0$, provided that the Al contact does not disturb the light illumination on the β-$FeSi_2$ surface. On the basis of these results, we conclude that the diffusion length obtained by EBIC was reproducible by OBIC, and also that β-$FeSi_2$ 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-β-$FeSi_2$ and discuss the mobility of holes. The diffusion length L is related to carrier lifetime τ and diffusion length L by the following expressions as $L=(D\tau)^{1/2}$ and $D=\mu kT/q$, where μ 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 β-$FeSi_2$ single crystal (AP63) using a 1.31 μm 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 μs. 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 $\lambda=1.55$ μm. In contrast, the longer decay time of approximately 2.7 μs remained unchanged. At larger photon energies ($\lambda=1.31$ μm), 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 I 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 β-$FeSi_2$ were obtained, we are able to calculate the hole mobility. When we use the diffusion length of 38 (EBIC) and 51 μm (OBIC), and the carrier lifetime of 2.7 μs, 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 β-$FeSi_2$ 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 β-$FeSi_2$ bulk has been reported to be in the range of 10–20 $cm^2/V\ s$.[19–21] We think

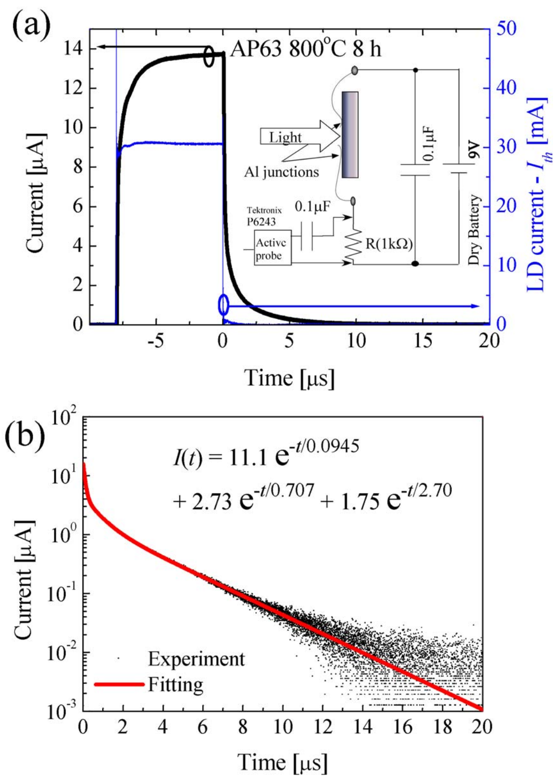

FIG. 3. (Color online) (a). Decay curve of photoconductivity (thick line) and LD drive current (thin line) with time measured at RT using a 1.31 μm light pulse. The measurement circuit was inserted. (b) Semilogarithmic plot of photoconductivity with time and fitting using three decay times.

that this discrepancy comes from surface damaged regions in β-$FeSi_2$ crystals. The short decay time observed in Fig. 3 and the fact that the long decay time became dominant for a longer-wavelength LD light, suggest the existence of surface damaged regions on the β-$FeSi_2$ crystals. Thus, we speculate that the Hall measurements might contain a certain amount of measurement errors. However, we have only limited information on the electrical properties of β-$FeSi_2$, and thus further discussion is necessary.

In conclusion, we have investigated the L and τ values of photogenerated minority carriers in n-type β-$FeSi_2$ crystals. The τ 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 μm, respectively. The hole mobility was calculated to be in the range of 200–360 $cm^2/V\ s$ at RT.

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