Abstract The energy relaxation of electrons in $\gamma$-In$_2$Se$_3$ nanorods was investigated by the excitation-dependent photoluminescence (PL). From the high-energy tail of PL, we determine the electron temperature ($T_e$) of the hot electrons. The $T_e$ variation can be explained by a model in which the longitudinal optical (LO)-phonon emission is the dominant energy relaxation process. The high-quality $\gamma$-In$_2$Se$_3$ nanorods may be a promising material for the photovoltaic devices.

Keywords InSe nanorods · Hot photoluminescence · Energy relaxation

Introduction

The III–VI semiconductors have been the subject of many investigations due to their peculiar electrical and optical properties, and their potential applications in electronic and optoelectronic devices [1–4]. Among these semiconductors, $\gamma$-In$_2$Se$_3$ has attracted attention because it is suitable for use in photovoltaic applications [5]. In the recent years, many researchers have been interested in the synthesis of the nanoscale materials due to their unique properties and novel applications in optoelectronic and electronic devices [6–8]. Although some progress has been achieved regarding the growth and characterization of $\gamma$-In$_2$Se$_3$ epilayers, the $\gamma$-In$_2$Se$_3$ nanostructures have not been grown and investigated yet. The $\gamma$-In$_2$Se$_3$ nanostructures may show potential applications in optoelectronic device such as lasers, light emitting diodes (LEDs), and solar cells, due to their high surface-to-volume ratio.

When excess energy is supplied to a carrier by optical excitation or an applied electric field, the energetic carrier becomes hot. The hot carriers then relax toward less energetic state by two competing processes, namely scatterings with other carriers and emission of phonons [9]. The understanding of this energy relaxation process constitutes a direct probe of a very fundamental interaction in condensed matter physics, namely, the electron–phonon and electron–electron interactions. Also, the subject is of obvious technological significance since many devices work mostly in high-field conditions. High electric fields may lead to carrier heating and, consequently, transport effects related to the hot carrier distribution function. A knowledge of hot carrier relaxation mechanisms is thus essential not only for understanding the fundamental process in semiconductor materials but also for evaluating optical device performance.
In this study, the single phase $\gamma$-In$_2$Se$_3$ nanorods on silicon (111) substrates were grown by metal-organic chemical vapor deposition (MOCVD). The excitation power dependence of photoluminescence (PL) in $\gamma$-In$_2$Se$_3$ nanorods was studied. The high-energy tails of the low-temperature PL were characterized by effective electron temperatures which increase with increasing excitation intensity. It is found the main path of energy relaxation of the hot electrons in the $\gamma$-In$_2$Se$_3$ nanorods is the LO-phonon emission.

Experiment

The $\gamma$-In$_2$Se$_3$ nanorods were grown on Si (111) substrates by using an MOCVD system at atmospheric pressure with a vertical reactor. The liquid MO, a TMIn compound, and gaseous H$_2$Se were employed as the reactant source materials for In and Se, respectively. The gaseous N$_2$ was used as the carrier gas in the process. The substrates used in this experiment were cut from a 6-inch $p$-type vicinal (111)-oriented Si wafer. Before the growth, Si substrates were baked at 1100 °C for 10 min in gaseous HCl and H$_2$ to remove the native oxide. After the thermal etching process, the reactor was cooled down to 425 °C and the $\gamma$-In$_2$Se$_3$ started to grow. The gaseous flow rate of TMIn was kept at 3 μmol/min and that of H$_2$Se was controlled at 40 μmol/min. The gaseous H$_2$Se was mixed with 85% hydrogen and 15% H$_2$Se. The $\gamma$-In$_2$Se$_3$ nanorods were grown at 425 °C during a total growth time of 50 min. The structure of the $\gamma$-In$_2$Se$_3$ nanorods was examined by the X-ray diffraction (XRD) in a $\theta$–$2\theta$ geometry. The XRD measurements were performed by using the CuKα-radiation ($\lambda$ = 1.541 Å) to test the phases of samples. PL was made using the Ar-ion laser operating at a wavelength of 514.5 nm. The room-temperature PL measurements were performed using a confocal microscopy. The collected luminescence was dispersed by a 0.75 m spectrometer and detected with a photo-multiplier tube (PMT).

Results and Discussion

The morphology of the grown $\gamma$-In$_2$Se$_3$ nanorods was investigated by the scanning electron microscopy (SEM). The cross-sectional image of SEM for the $\gamma$-In$_2$Se$_3$ nanorods is shown in Fig. 1, indicating a high density and narrow size distribution. The crystallographic face of each nanorod is shown in the inset of Fig. 1, revealing the hexagonal top end of the $\gamma$-In$_2$Se$_3$ nanorods. The inset of Fig. 2 shows the XRD pattern of $\gamma$-In$_2$Se$_3$ nanorods. A high intensity of the XRD pattern from the Si (111) plane was clearly observed at $2\theta = 28.44^\circ$. Furthermore, the XRD reflection from the plane of $\gamma$-In$_2$Se$_3$ was also observed at $2\theta = 27.59^\circ$, confirming the hexagonal single phase for the $\gamma$-In$_2$Se$_3$ nanorods [10]. The 300-K PL spectrum of the $\gamma$-In$_2$Se$_3$ nanorods is shown in Fig. 2. A clear PL peak was observed with the peak position of 1.95 eV, corresponding to the near band gap edge emission [11]. Observation of the room-temperature luminescence of the $\gamma$-In$_2$Se$_3$ nanorods indicates the good quality of our sample.

In the process of the hot PL, the photoexcitation creates energetic electrons in the conduction band, which relax toward less energetic state by transferring energy to the lattice (via the electron–phonon scattering) and other electrons (via the electron–electron scattering). If the electron–electron collision rate is larger than the phonon emission rate, then the non-equilibrium electron population in the electron gas relaxes toward a Maxwell distribution and can be characterized by an $T_e$ ($T_c$) which is higher than the lattice temperature ($T_l$) [12]. Figure 3(a–d) shows the high-energy tail of the 15-K PL in $\gamma$-In$_2$Se$_3$ nanorods with
different excitation power densities. The spectra show that
the high-energy tail of each PL decreases exponentially
with photon energy, revealing that the PL is related to the
hot carrier recombination. The high-energy tail of each PL
in Fig. 3 can be analyzed by the function [6]:
\[ I(h\nu) \sim \exp(-h\nu/E_0), \tag{1} \]
where \( E_0 \) is the specific energy. With low excitation power,
\( E_0 \) reflects the sample quality at low temperatures [6].
Under higher photoexcitation, \( E_0 \) can reflect the kinetic
energy of the thermalized electrons and a well-defined \( T_e \)
can be extracted. We have fitted the high-energy tail of PL
using Eq. 1, as shown by the solid lines in Fig. 3.

The inverse \( T_e \) versus the excitation power is plotted as
the open squares in Fig. 4. The slope of the inverse \( T_e \),
displayed as the solid line, corresponds to a value of
19 meV. To find out whether this energy is related to the
phonon energy in \( \gamma \)-In$_2$Se$_3$ nanorods, we performed the
Raman scattering measurements. Figure 4 is the Raman
spectrum of \( \gamma \)-In$_2$Se$_3$ nanorods, displaying a clear peak
located at 152 cm$^{-1}$, whose energy corresponds
to \( \sim \) 19 meV. Thus, the energy extracted from the slope of
the inverse \( T_e \) is in good agreement with the phonon energy
measured from the Raman scattering. This indicates the
phonon scattering is very efficient in transferring energy
from electrons to the lattice. In other words, the phonon
emission is the dominant energy loss mechanism in the
energy relaxation processes of hot electrons in \( \gamma \)-In$_2$Se$_3$
nanorods.

To obtain the energy loss rate per electron from experi-
ments, the power balance equations were used. As the
steady-state electron population increases by increasing the
excitation density, enhanced electron–electron scattering
results in a larger fraction of the available energy being
shared with the electron gas. Thus, the \( T_e \) is determined by
balancing the rate of generation for the energetic electrons
with the rate of energy loss from the electrons to the lattice.
For the photoexcitation, the pump power per electron \( P_e \)
given to the electron is [12]
\[ P_e = \frac{I W}{d \hbar \nu_0 n}, \tag{2} \]
where \( I \) is the laser power absorbed per unit area, \( d \) is the
absorption length at laser energy, \( n \) is the carrier
concentration, and \( W \) is the part of the photon excess
energy obtained by electron. The carrier concentration \( n \)
was obtained from the room-temperature Hall-effect
measurements. The open square in Fig. 5 displays the \( T_e \)
as a function of the power input per electron \( (P_e) \). If we
assume the dominant process for this relaxation is through
LO-phonon emission and \( T_e \) is much larger than \( T_l \), then
the energy loss rate per electron due to the LO-phonon
scattering can be given by [13],
\[ P(T_e) = \left( \frac{E_{LO}}{\tau_{ph}} \right) \left( \frac{e^{\nu_0 - \nu_e} - 1}{e^{\nu_0} - 1} \right) \left[ \frac{e^{\nu_e}/2K_0(\nu_e/2)}{\sqrt{\pi}/\nu_e} \right], \tag{3} \]
where $\tau_{\text{ph}}$ is the effective phonon lifetime, $E_{\text{LO}}$ is the LO-phonon energy, $x_0 = \frac{E_{\text{LO}}}{k_B T_l}$, $x_e = \frac{E_{\text{LO}}}{k_B T_e}$, and $K_0$ is the modified Bessel function of the order of zero. In the steady state, the power input per electron $P_e$ is equal to the power loss to the lattice through phonon scattering. Taking values of 19 meV, $1.12 \times 10^{16}$ cm$^{-3}$, 2.12, 2.41 eV, $4.8 \times 10^{-6}$ cm for $E_{\text{LO}}$, $n$, $W$, $h\nu_0$, $d$, respectively, the solid line in Fig. 4 displays the fitted $T_e$ with the power loss per electron. Good agreement between experiments and calculations indicates that the model based on the carrier scattering by LO-phonon is able to explain the measured $T_e$ variation with excitation power. It demonstrates again that the LO-phonon emission is the dominant energy loss mechanism in the energy relaxation processes of hot electrons in $\gamma$-In$_2$Se$_3$ nanorods.

Summary

In summary, the $\gamma$-In$_2$Se$_3$ nanorods were successfully grown on Si (111) substrates by using MOCVD. A clear room-temperature PL with the peak position of 1.95 eV was observed, corresponding to the near band edge emission. The high-energy tail of PL can be characterized by an effective $T_e$ which increases with increasing excitation intensity. The relationship between the $T_e$ and the electron energy loss rate can be explained by a model based on the carrier scattering by the LO-phonons.

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References