Observation of temperature-dependent heavy- and light-hole split direct bandgap and tensile strain from $\text{Ge}_{0.985}\text{Sn}_{0.015}$ using photoreflectance spectroscopy

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Temperature- (T-) dependent photoreflectance (PR) measurements have been made for the tensile-strained, undoped $\text{Ge}_{0.985}\text{Sn}_{0.015}$ film grown on *n*-Si substrate by ultra-high vacuum chemical vapor deposition method. The PR spectra at room temperature consist of two signals at around 0.739 and 1.022 eV, which are assigned to the direct transitions from conduction Γ valley to valence and spin-orbit split-off bands, respectively. The T-dependent PR measurements show tensile-strain split direct bandgap transitions from the Γ valley to the light-hole (E_{LH}) and heavy-hole (E_{HH}) bands at energies of 0.772 and 0.803 eV at 12 K, respectively, which are not usually observable from the photoluminescence measurements for relatively high Sn content $\text{Ge}_{1-y}\text{Sn}_y$ samples. The PR signals for both HH and LH bands are blue shifted and their intensities decrease with increasing temperature, but both LH and HH PR signals persist through 240 K and only one HH PR signal is observed at room temperature. It has been observed that the separation energy between the E_{HH} and E_{LH} increases as T decreases, which clearly indicates an increase in tensile strain as T decreases. From the analysis of the T-dependent separation energy between the E_{LH} and E_{HH} , the T-dependent tensile strain in the $\text{Ge}_{0.985}\text{Sn}_{0.015}$ film was obtained, which might not be easily measured using the X-ray diffraction method.

1. Introduction

Silicon has been used for its electronic device and integrated circuit applications for many decades, but it is a very poor light emitting source due to its indirect bandgap nature. Therefore, in recent decades, intensive research has been pursued to develop Si- and Ge-based direct bandgap semiconductors such as Ge, $\text{Ge}_{1-y}\text{Sn}_y$, and $\text{Ge}_{1-x-y}\text{Si}_x\text{Sn}_y$ films grown on Si or Ge substrates to expand its functionalities well beyond electronics to possible new optoelectronic devices [1-8]. Many research groups have reported the photoluminescence (PL) results of the tensile strained Ge and $\text{Ge}_{1-y}\text{Sn}_y$ alloys [9-13], and the electroluminescence (EL) emissions of direct bandgap from various Ge- and $\text{Ge}_{1-y}\text{Sn}_y$ -based diode structures [6,11]. In spite of the great recent progress in the crystal growth methods of $\text{Ge}_{1-y}\text{Sn}_y$ alloys on Si substrate, the as-grown alloys often required a post-growth annealing treatment to improve its crystallinity. However, the annealed $\text{Ge}_{1-y}\text{Sn}_y/\text{Si}$ alloys could have a biaxial tensile strain upon cooling [14,15].

An enhancement in PL intensity has been observed for the tensile strained Ge film in the near-infrared regime compared to bulk Ge due to the shrinkage of the direct bandgap [16,17]. In addition, tensile strain causes the splitting of light-hole (LH) and heavy-hole (HH) valence bands of $\text{Ge}_{1-y}\text{Sn}_y$ [12,18]. Only a few researchers have reported the separation between LH and HH valence bands for the Ge and the $\text{Ge}_{1-y}\text{Sn}_y$ films at room temperature through photoreflectance (PR) spectroscopy so far [12,18,19]. Although the direct bandgap energies of strained $\text{Ge}_{1-y}\text{Sn}_y$ films grown on Si occurring between the conduction band Γ valley and LH- and HH-valence bands could be calculated as a function of in-plane strain, the theoretical calculation of the tensile strain is difficult after the annealing process. In general, the strain is calculated by using rocking curves of a high resolution X-ray diffraction (HRXRD), but the measurements are difficult at low temperatures. Alternatively, Thomas *et al.* reported temperature dependent strain on a ZnSe/GaAs using PR measurements [20]. Although several PR papers for the strained $\text{Ge}_{1-y}\text{Sn}_y/\text{Si}$ alloys have been reported at room temperature, there have hardly been any reports on the temperature dependent tensile strain and separation energy between HH- and LH-valence bands for the $\text{Ge}_{1-y}\text{Sn}_y/\text{Si}$ alloys using

the PR measurements. In this paper, the PR results of direct bandgap transition energies between Γ conduction valley and LH- and HH-valence bands in the biaxial tensile-strained $\text{Ge}_{0.985}\text{Sn}_{0.015}/\text{Si}$ are reported as a function of sample temperature, as well as the calculated results of the temperature-dependent tensile strain from the energy separation between LH and HH optical transitions.

2. Experiment

The undoped $\text{Ge}_{0.985}\text{Sn}_{0.015}$ film was grown by using an ultra-high vacuum chemical vapor deposition method directly on *n*-type Si substrate with $\rho = 0.005 \text{ } \Omega\text{-cm}$ via deuterated stannane (SnD_4) assisted reactions of pure digermane (Ge_2H_6) at an optimum growth temperature of 375°C and at a pressure of 0.4 Torr. The content of 1.5% Sn and a film thickness of 620 nm were estimated from Rutherford backscattering (RBS) measurements. The as-grown $\text{Ge}_{0.985}\text{Sn}_{0.015}$ film was annealed at 750°C for 30 min in a hydrogen environment, which resulted in the improved crystallinity of the sample greatly as observed from the narrowing of the XRD peak (not shown here). Apparently, the annealing process reduces the levels of threading defects. The strain in the as-grown $\text{Ge}_{0.985}\text{Sn}_{0.015}$ epitaxial layer was initially slightly compressive. However, the sample became fully relaxed after the annealing treatment, and then changed to slightly tensile strain upon cooling to room temperature due to the large difference in thermal expansion coefficients between $\text{Ge}_{0.985}\text{Sn}_{0.015}$ and Si [21,22]. The lattice constants were estimated using 224 reciprocal space maps measured by HRXRD, yielding $a=5.6801 \text{ } \text{\AA}$ and $c= 5.6583 \text{ } \text{\AA}$. The latter is similar to the value $c=5.6587 \text{ } \text{\AA}$ obtained from 004 on-axis peaks. The final residual tensile strain value was estimated to be 0.20% according to HRXRD measurement. More detailed descriptions of $\text{Ge}_{1-y}\text{Sn}_y$ crystal growth and annealing temperatures can be found from references [9] and [23], and those of RBS and HRXRD measurements can be obtained from references [23] and [24].

PR measurements were performed using a 637 nm laser diode as an excitation source with the excitation intensity of 400 mW/cm^2 , and the PR signals were detected by an extended InGaAs detector (1,000-2,400 nm). The probe light was a monochromatic beam obtained from a tungsten-halogen lamp dispersed through a monochromator. PR spectra were

measured at temperatures ranging from 12 to 300 K. A more detailed description of the PR setup can be found in Ref. 25.

3. Results and discussion

The PR spectra of undoped as-grown and annealed $\text{Ge}_{0.985}\text{Sn}_{0.015}$ films grown on n -Si substrate are shown in Fig. 1. The inset of the figure shows the PR spectrum of a p-type bulk Ge, which was used as a reference sample. The measurements were performed at 300 K with a laser excitation intensity of 400 mW/cm^2 . The PR spectrum for the as-grown undoped $\text{Ge}_{0.985}\text{Sn}_{0.015}$ film exhibits a broad PR spectrum (black color), which may indicate slightly poor crystal quality for this film. On the other hand, the PR spectrum of the thermally annealed $\text{Ge}_{0.985}\text{Sn}_{0.015}$ film (red color) shows very clear and specific features of spectrum. This result indicates that the crystal quality of the $\text{Ge}_{0.985}\text{Sn}_{0.015}$ film improves greatly after thermal annealing. These PR observations agree with the fact that in general, the PR spectra of doped or poor quality semiconductors are broad, and the PR spectra of undoped, good quality semiconductors show sharp and specific features.

The PR spectrum of annealed $\text{Ge}_{0.985}\text{Sn}_{0.015}/n\text{-Si}$ is mainly composed of two transition signals located at around 0.75 and 1.03 eV. For the bulk Ge sample, the direct bandgap transition PR signal was obtained at around 0.80 eV as shown in the inset of Fig. 1, which is in good agreement with the direct transition energy (E_D) of the Ge [26]. Also, the direct transition from the Γ valley in conduction band to the spin-orbit split-off band (E_{SO}) was observed approximately at 1.09 eV for this bulk Ge sample. In light of the positions of the E_D and E_{SO} transition signals for the bulk Ge sample, the PR signals at around 0.75 and 1.03 eV obtained from the undoped annealed $\text{Ge}_{0.985}\text{Sn}_{0.015}$ film are attributed to the direct bandgap transition and the spin-orbit split-off band transition, respectively. The smaller direct bandgap transition energy of the undoped $\text{Ge}_{0.985}\text{Sn}_{0.015}$ sample ($E_D \approx 0.75 \text{ eV}$) compared to the bulk Ge sample ($E_D \approx 0.8 \text{ eV}$) is attributed to the 1.5% Sn concentration and 0.20% tensile strain induced by the thermal expansion mismatch between $\text{Ge}_{0.985}\text{Sn}_{0.015}$ and Si substrate during cooling to room temperature. These direct transitions for Ge and various $\text{Ge}_{1-y}\text{Sn}_y$ alloys have also been reported by several groups [14,15,27-31]. It is also worthwhile to point out that, the indirect bandgap related PR signal was not observed either from the bulk Ge or the annealed $\text{Ge}_{0.985}\text{Sn}_{0.015}/n\text{-Si}$ samples. In the case of indirect bandgap semiconductors, the PR signal is

usually dominated by signals from the direct bandgap transition because of relatively inefficient indirect bandgap related re-emission. Therefore, it is often difficult to observe any PR spectrum related to the indirect transition.

In order to determine the direct bandgap transition energy of E_D , the third-derivative of Lorentzian form was used to analyze the line shape of PR signal. Under low electric field condition, the line shape of the PR spectrum is given by [32]

$$\frac{\Delta R}{R} = \sum_{j=1}^n \text{Re}[C_j e^{i\varphi_j} (E - E_j + i\Gamma_j)^{-m}], \quad (1)$$

where C_j and φ_j are amplitude and phase factors, respectively. E_j is the transition energy, E is the photon energy, Γ_j is the broadening parameter, and m is the line-shape factor. The factor m is chosen to be 2.5, which represents a three-dimensional critical point. The calculated E_D and E_{SO} are 0.739 and 1.022 eV, respectively. At room temperature, the E_D between the conduction Γ valley and the valence band for unstrained $\text{Ge}_{1-x}\text{Sn}_x$ is given as a function of Sn concentration by the following equation [33].

$$E_g(\text{Ge}_{1-x}\text{Sn}_x) = (1 - x)E_g(\text{Ge}) + xE_g(\text{Sn}) - bx(1 - x), \quad (2)$$

where the direct transition energies of Ge and Sn are 0.80 and -0.41 eV, respectively, and the bowing parameter b used is 2.42 eV [33]. The calculated direct transition energy of $\text{Ge}_{0.985}\text{Sn}_{0.015}$ film from Eq. (2) is approximately 0.746 eV. The E_D (0.739 eV) obtained from Eq. (1) is slightly lower than that from Eq. (2) due to the presence of biaxial tensile strain (0.20%).

Temperature-dependent PR measurement was performed for the annealed $\text{Ge}_{0.985}\text{Sn}_{0.015}$ film and the results are shown in Fig. 2. The E_D and E_{SO} positions are blue-shifted as temperature decreases from room temperature due to increases in direct bandgap and spin-orbit split-off band energies by lattice shrinkage. More importantly, the weaker signal below the dominant PR signal is gradually separated from the main signal and the weaker signal becomes much more distinct as temperature decreases further to low temperatures as shown in the figure. The two PR signals (e.g., 0.772 and 0.803 eV at 12 K) are attributed to the direct bandgap energy transitions from the conduction Γ valley to the LH and HH valence bands. In

case of thin film under biaxial tensile strain, the degeneracy of LH and HH bands is broken, and the separation energy between the LH and HH bands increases as the tensile strain increases due to increased thermal expansion mismatch with decreasing temperature [15]. This is clearly shown in Fig. 2(a) for the tensile strained $\text{Ge}_{0.985}\text{Sn}_{0.015}$ sample as marked in arrows, where the direct bandgap transition signal for the LH band occurs at lower energy than that for the HH band. However, the transition signal to the LH band is observed at a higher energy than that to the HH band for the compressively strained $\text{Ge}_{1-y}\text{Sn}_y$ sample [33]. This observation of clear separation between the LH and HH bands through the T-dependent PR measurements are particularly note worthy for this 1.5% Sn content sample because the separation of LH and HH peaks was not observed by PL measurements. In general, the separation of LH and HH PL peaks are hardly observed by PL method even for a relatively higher Sn content sample. For example, the observation of the separated LH and HH PL peaks were reported from the tensile-strained GeSn with only 0.03% Sn content at below the room temperature [15]. The photoreflection consists of both absorption and re-emission and the amplitude of the PR signal depends on the number of density states. Therefore, the PR signal of the HH band is much stronger than that of the LH band due to the higher density of states in the HH band. It is observed that the PR signals for both HH and LH bands decrease with increasing temperature. The split of LH and HH PR signals persists through 240 K and only one PR signal for HH band is observed at room temperature.

Temperature-dependence of the direct bandgap transition energies from the conduction Γ valley to the LH (E_{LH}) and HH (E_{HH}) bands of $\text{Ge}_{0.985}\text{Sn}_{0.015}$ thin film are calculated from the analysis of the line shape of PR signal by Eq. (1), and the results are plotted in Fig. 2(b). Also, the energy separation between the E_{HH} and E_{LH} is plotted in the inset of Fig. 2(b) as a function of temperature. It is clearly seen in the figure that both the E_{LH} and E_{HH} (0.772 and 0.803 eV, respectively, at 12 K) decrease with increasing temperature due to bandgap shrinkage and decrease in tensile strain of the film. Also, the energy separation (~ 30 meV at 12 K) between the E_{HH} and E_{LH} decreases as temperature increases to room temperature (~ 21 meV at 240 K) due to decreasing tensile strain as shown in the inset of Fig. 2(b). This observation is consistent with the PL results observed from 0.03% Sn GeSn sample [15]. The data for the HH and LH transition energies in Fig. 2(b) are well fitted with Varshni's type equation [34]

$$E_D(T) = E_D(0) - \frac{\alpha T^2}{T + \beta}, \quad (3)$$

where α and β are fitting constants of a given material. The fitting parameters used for the fitting curve are listed in Table I. The α and β fitting values are slightly different from those of the bulk Ge due to the strain and Sn content of the $\text{Ge}_{0.985}\text{Sn}_{0.015}$ thin film.

According to deformation potential theory, the E_{LH} and E_{HH} are given by the following two equations [18]:

$$E_{\text{LH}} = E_g^\Gamma(0) + a(\varepsilon_\perp + 2\varepsilon_\parallel) + \frac{\Delta_0}{2} - \frac{1}{4}\delta E_{100} - \frac{1}{2}\sqrt{\Delta_0^2 + \Delta_0\delta E_{100} + \frac{9}{4}(\delta E_{100})^2}, \quad (4a)$$

$$E_{\text{HH}} = E_g^\Gamma(0) + a(\varepsilon_\perp + 2\varepsilon_\parallel) + \frac{1}{2}\delta E_{100}, \quad (4b)$$

$$\delta E_{100} = 2b(\varepsilon_\perp - \varepsilon_\parallel), \quad (4c)$$

where E_{LH} and E_{HH} are the direct transition energies from the bottom of the conduction Γ valley to the top of the LH and HH valence bands under an in-plane strain ($\varepsilon_\parallel$), respectively, and $\varepsilon_\perp$ is the perpendicular strain to the film. $E_g^\Gamma(0)$ is the direct transition energy of unstrained bulk Ge at room temperature. Δ_0 is the energy separation from the top of the valence band to the spin-orbit split-off band. a and b are deformation potential constants at room temperature. The above relations clearly show that the E_{LH} and E_{HH} depend on both the strain and the elastic constants in the $\text{Ge}_{0.985}\text{Sn}_{0.015}$ film and conversely, strain depends on the E_{LH} and E_{HH} , all of which are also temperature dependent. The difference between the E_{HH} and E_{LH} is given by

$$\Delta E = E_{\text{HH}} - E_{\text{LH}} = -\frac{\Delta_0}{2} + \frac{3}{4}\delta E_{100} + \frac{1}{2}\sqrt{\Delta_0^2 + \Delta_0\delta E_{100} + \frac{9}{4}(\delta E_{100})^2}, \quad (5)$$

where $\delta E_{100} = 2b(\varepsilon_\perp - \varepsilon_\parallel)$ as shown in Eq. (4c). Using this equation, the strain can be calculated from the estimated separation energy of ($E_{\text{HH}} - E_{\text{LH}}$), which was calculated from the analysis of the line shape of the measured PR signals. A value of 0.276 eV was used for

Δ_0 , which was obtained from the energy difference between the E_{SO} (1.022 eV from Eq. (1)) and $E_g(Ge_{1-x}Sn_x)$ (0.746 eV from Eq. (2)) for the unstrained film. In the calculation, the bulk Ge values of $\varepsilon_{\parallel}/\varepsilon_{\perp}=-1.33$ [18] and $b=-2.55$ eV [36], which are assumed to be independent of the temperature, were used as a good approximation for current sample. The calculated results for the temperature-dependent tensile strains using the measured separation energy of ($E_{HH} - E_{LH}$) from PR signals are plotted in Fig. 3. The tensile strain ($\sim 0.32\%$ at 12 K) decreases with increasing temperature as reflected from the decreased splitting of the LH and HH bands. In addition, tensile strain values were theoretically calculated using the T-dependent thermal expansivities of bulk Ge and Si, and the results are plotted as a solid (red) line in Fig. 3. The calculation assumed a room temperature strain value of 0.20 % which was estimated from the HRXRD measurements for this sample. As seen in the figure, the tensile strain determined from the PR results is slightly larger than the theoretical values, however the overall trend agrees well. It is important to point out that the temperature-dependent tensile strain of $Ge_{1-x}Sn_x$ could be estimated through the PR measurements as this paper indicates. More accurate estimation can be obtained from the accurate measurement of separation energy between the E_{HH} and E_{LH} values, and from the accurately known physical parameters of $Ge_{1-x}Sn_x$ including accurate deformation potential.

4. Conclusion

The temperature-dependent heavy- and light-hole direct bandgap energies and tensile strain of undoped $Ge_{0.985}Sn_{0.015}$ film grown on n -Si substrate have been investigated by using photoreflectance (PR) spectroscopy measurements. The PR spectrum for the as-grown $Ge_{0.985}Sn_{0.015}$ film exhibits a broad spectrum, whereas that for the thermally annealed film shows very clear and specific features of spectrum, indicating a great improvement of the crystal quality of the film after thermal annealing at 750°C for 30 min. The annealed $Ge_{0.985}Sn_{0.015}$ film shows two optical transition signals at around 0.739 and 1.022 eV at 300 K, which are assigned to the direct transition energies from the conduction Γ valley to heavy-hole (HH) valence and spin-orbit (SO) split-off (E_{SO}) bands, respectively. The direct transition energy positions determined from the analysis of the line shape of PR signal are blue-shifted as the temperature decreases due to increase in direct bandgap and SO split-off

band energies by lattice shrinkage. Also, two PR signals of tensile strain-split direct bandgap transitions (e.g., 0.772 and 0.803 eV at 12 K) are observed at low temperatures, and they are attributed to transition energies from the Γ valley to the light-hole (LH), E_{LH} , and heavy-hole bands, E_{HH} , where the energy value of E_{LH} is lower than that of E_{HH} . The PR signal of the HH valence band is much stronger than that of the LH band due to the higher density of states in the HH band. The evolution of the T-dependent PR results clearly shows that the separation energy between the LH and HH bands increases gradually (e.g., from ~21 meV at 240 K to ~30 meV at 12 K) as the tensile strain increases due to increased thermal expansion mismatch with decreasing temperature. This HH and LH valence band split is not usually observable from the PL measurements even for relatively high Sn content $\text{Ge}_{1-y}\text{Sn}_y$ samples. The PR signal intensities for both HH and LH bands decrease with increasing temperature, persist through 240 K, and only the strong HH PR signal is observed at room temperature. The T-dependent tensile strain in the $\text{Ge}_{0.985}\text{Sn}_{0.015}$ film was obtained by analyzing the T-dependent separation energy between the E_{LH} and E_{HH} . The obtained values agree well with the theory and with the room temperature value of 0.20% estimated from the HRXRD measurements. It is important to point out that the T-dependent tensile strain of GeSn could be relatively accurately estimated through the PR measurements instead of the XRD method.

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References

- [1] R. A. Soref, C. H. Perry, J. Appl. Phys. 69 (1991) 539.
- [2] Y. Maeda, N. Tsukamoto, Y. Yazawa, Y. Kanemitsu, Y. Masumoto, Appl. Phys. Lett. 59 (1991) 3168.
- [3] Y. Nakamura, K. Watanabe, Y. Fukuzawa, M. Ichikawa, Appl. Phys. Lett. 87 (2005) 133119.
- [4] C. Xu, L. Jiang, J. Kouvetakis, J. Menendez, Appl. Phys. Lett. 103 (2013) 072111.
- [5] Y. Nakamura, A. Masada, M. Ichikawa, Appl. Phys. Lett. 91 (2007) 013109.
- [6] J. P. Gupta, N. Bhargava, S. Kim, T. Adam, J. Kolodzey, Appl. Phys. Lett. 102 (2013) 251117.
- [7] R. E. Camacho-Aguilera, Y. Cai, N. Patel, J. T. Bessette, M. Romagnoli, L. C. Kimerling, J. Michel, Opt. Express 20 (2012) 11316.
- [8] M. Oehme, M. Schmid, M. Kaschel, M. Gollhofer, D. Widmann, E. Kasper, J. Schulze, Appl. Phys. Lett. 101 (2012) 141110.
- [9] J. Mathews, R. T. Beeler, J. Tolle, C. Xu, R. Roucka, J. Kouvetakis, J. Menéndez, Appl. Phys. Lett. 97 (2010) 221912.
- [10] M.-Y. Ryu, T. R. Harris, Y. K. Yeo, R. T. Beeler, J. Kouvetakis, Appl. Phys. Lett. 102 (2013) 171908.
- [11] S.-L. Cheng, J. Lu, G. Shambat, H.-Y. Yu, K. Saraswat, J. Vuckovic, Y. Nishi, Opt. Express 17 (2009) 10019.
- [12] Y. Ishikawa, K. Wada, J. Liu, D. D. Cannon, H.-C. Luan, J. Michel, L. C. Kimerling, J. Appl. Phys. 98 (2005) 013501.
- [13] R. Jakomin, M. de Kersauson, M. El Kurdi, L. Largeau, O. Mauguin, G. Beaudoin, S. Sauvage, R. Ossikovski, G. Ndong, M. Chaigneau, I. Sagnes, P. Boucaud, Appl. Phys. Lett. 98 (2011) 091901.
- [14] D. D. Cannon, J. Liu, Y. Ishikawa, K. Wada, D. T. Danielson, S. Jongthammanurak, J.

- Michel, L. C. Kimerling, *Appl. Phys. Lett.* 84 (2004) 906.
- [15] T. R. Harris, Y. K. Yeo, M.-Y. Ryu, R. T. Beeler, J. Kouvetakis, *J. Appl. Phys.* 116 (2014) 103502.
- [16] Y. Huo, H. Lin, R. Chen, M. Makarova, Y. Rong, M. Li, T. I. Kamins, J. Vuckovic, J. S. Harris, *Appl. Phys. Lett.* 98 (2011) 011111.
- [17] T. H. Cheng, K. L. Peng, C. Y. Ko, C. Y. Chen, H. S. Lan, Y. R. Wu, C. W. Liu, H. H. Tseng, *Appl. Phys. Lett.* 96 (2010) 211108.
- [18] J. Liu, D. D. Cannon, K. Wada, Y. Ishikawa, D. T. Danielson, S. Jongthammanurak, J. Michel, L. C. Kimerling, *Phys. Rev. B* 70 (2004) 155309.
- [19] R. Roucka, J. Mathews, V. R. D’Costa, J. Xie, J. Tolle, S.-Q. Yu, J. Menendez, J. Kouvetakis, *J. Vac. Sci. Technol. B* 26 (2008) 1952.
- [20] R. J. Thomas, B. Rockwell, H. R. Chandrasekhar, M. Chandrasekhar, A. K. Ramdas, M. Kobayashi, R. L. Gunshor, *J. Appl. Phys.* 78 (1995) 6569.
- [21] V. R. D’Costa, Y. Fang, J. Mathews, R. Roucka, J. Tolle, J. Menéndez, J. Kouvetakis, *Semicond. Sci. Technol.* 24 (2009) 115006.
- [22] R. Roucka, R. Beeler, J. Mathews, M.-Y. Ryu, Y. K. Yeo, J. Menéndez, J. Kouvetakis, *J. Appl. Phys.* 109 (2011) 103115.
- [23] G. Grzybowski, R. T. Beeler, L. Jiang, D. J. Smith, J. Kouvetakis, J. Menendez, *Appl. Phys. Lett.* 101, (2012) 072105.
- [24] H.-J. Jo, M. G. So, J. S. Kim, M.-Y. Ryu, Y. K. Yeo, J. Kouvetakis, *Thin Solid Films* 591 (2015) 295.
- [25] J. S. Kim, P. W. Yu, S. K. Noh, J. I. Lee, J. S. Kim, S. M. Kim, G. H. Kim, S.-K. Kang, S. G. Kim, J. S. Son, J. Y. Leem, *J. Korean Phys. Soc.* 39 (2001) 246.
- [26] O. Madelung, *Data in Science and Technology: Semiconductors Other Than Group IV Elements and III–V Compounds*, Springer-Verlag, Berlin, 1992.
- [27] V. R. D’Costa, C. S. Cook, A. G. Birdwell, C. L. Littler, M. Canonico, S. Zollner, J. Kouvetakis, J. Menendez, *Phys. Rev. B* 73 (2006) 125207.

- [28] S. Gupta, B. Magyari-Köpe, Y. Nishi, K. C. Saraswat, J. Appl. Phys. 113 (2013) 073707.
- [29] J. D. Gallagher, C. L. Senaratne, J. Kouvetakis, J. Menéndez, Appl. Phys. Lett. 105 (2014) 142102.
- [30] L. Jiang, J. D. Gallagher, C. L. Senaratne, T. Aoki, J. Matthews, J. Kouvetakis, J. Menéndez, Semicond. Sci. Technol. 29 (2014) 115028.
- [31] S. A. Ghetmiri, W. Du, J. Margetis, A. Mosleh, L. Cousar, B. R. Conley, L. Domulevich, A. Nazzal, G. Sun, R. A. Soref, J. Tolle, B. Li, H. A. Naseem, S.-Q. Yu, Appl. Phys. Lett. 105 (2014) 151109.
- [32] D. E. Aspnes, A. A. Studna, Phys. Rev. B 7 (1973) 4605.
- [33] H. Lin, R. Chen, W. Lu, Y. Huo, T. I. Kamins, J. S. Harris, Appl. Phys. Lett. 100 (2012) 102109.
- [34] Y. P. Varshni, Physica 34 (1967) 149.
- [35] M. E. Levinshsten, S. L. Rumyantsev, M. Shur, Handbook Series on Semiconductor Parameters, Volume 1: Si, Ge, C (Diamond), GaAs, GaP, GaSb, InAs, InP, InSb (World Scientific, London, 1996).
- [36] C. G. Van de Walle, Phys. Rev. B 39 (1989) 1871.

Table

Table 1. Calculated results of $\text{Ge}_{0.985}\text{Sn}_{0.015}$ thin film using Varshni equation.

Figure caption

Fig. 1. Photoreflectance spectra of as-grown and annealed $\text{Ge}_{0.985}\text{Sn}_{0.015}/\text{Si}$ thin films measured at room temperature. The inset is the PR spectrum of a bulk Ge.

Fig. 2. (a) Temperature-dependent photoreflectance spectra of the $\text{Ge}_{0.985}\text{Sn}_{0.015}/\text{Si}$ thin film, showing heavy-hole, light-hole and split-off band direct bandgap transitions. (b) Light- (E_{LH}) and heavy-hole (E_{HH}) direct bandgap transition energies obtained from PR spectra are plotted as a function of temperature from 12 to 300 K. The fitting curves are calculated using Varshni's type equation. The energy difference between the E_{HH} and E_{LH} is plotted in the inset.

Fig. 3. Temperature-dependence of the tensile strain obtained by analyzing the separation between the E_{LH} and the E_{HH} . The red line represents the theoretically calculated values.

Table 1. Calculated results of $\text{Ge}_{0.985}\text{Sn}_{0.015}$ thin film using Varshni equation.

	E (0) [eV]	α [10^{-4} eV/K]	β [K]
Direct bandgap of bulk Ge [35]	0.853	5.82	296
Heavy-hole (E_{HH})	0.804	4.20	284
Lighy-hole (E_{LH})	0.774	2.95	237
Split-off band (E_{SO})	1.086	4.43	327

Fig. 1.

Fig. 2.

Fig. 3.