Optoelectronic properties for the compressively strained Ge$_{1-x}$Sn$_x$ films grown on Ge(004)

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Abstract

Compressively strained Ge$_{1-x}$Sn$_x$ films ($x = 0.04, 0.08, 0.14$) have been grown on Ge(004) substrates by Molecular Beam Epitaxy. The wavelength dependence of the refractive index is deduced as $n(x, \lambda) = n_{\text{Ge}}(\lambda) + (-2 + 3.5 \lambda)x + 5(1-\lambda)x^2$ in the near-infrared range (NIR) (800–1700 nm) for Ge$_{1-x}$Sn$_x$ alloy films. That is similar to Si$_{1-x}$Ge$_x$ alloy films. The Hall measurement shows that the donor levels decrease due to dislocation at room temperature. Temperature dependence of the electron mobility for Ge$_{1-x}$Sn$_x$ films reveals that strain-induced defects lower the carrier mobility from 10 K to 310 K. The maximum carrier mobility reaches 2082 cm$^2$/Vs at $T = 122$ K for Ge$_{0.96}$Sn$_{0.04}$/Ge film. These results indicate that Sn-doping has great influences on electronic properties for Ge$_{1-x}$Sn$_x$ alloys. Our investigations may be helpful for fabricating the high performance optoelectronic devices.

1. Introduction

Ge$_{1-x}$Sn$_x$ alloys are promising IV semiconductors because of its tunable band gap structure and high carrier mobility, which can be induced by Sn content. These alloys have been successfully applied to the advanced devices in recent years [1, 2]. The refractive index of thin films correlates to the band gap energies and the optical absorption of semiconductor [3, 4]. High carrier mobility can contribute to improving the speed of the field effect transistors. The Optical and electronic properties of semiconductor alloys are related to the structure of the films, including the degree of strain, surface roughness, dislocation density, etc [5–8]. Effects of the structure on optoelectronic properties for GeSn films are still elusive. Therefore, it is necessary to explore the influence of microstructure on properties for GeSn films before the design of the optoelectronic devices. Spectroscopic Ellipsometer (SE), Hall experiments and theoretical methods are used to investigate the photoelectric properties of GeSn alloys [9–13]. Ge$_{1-x}$Sn$_x$ alloys were also studied by SE measurements [14, 15], Hall experiments and theoretical calculations [16–20]. SE has been used to investigate the electronic band structure. Moto et al. reported that the maximum mobility for polycrystalline Ge$_{1-x}$Sn$_x$ alloys appeared at Sn composition 0.032 which was slightly above the solubility of Sn in Ge [21]. Researches also suggested that the hole mobility for polycrystalline Ge$_{0.98}$Sn$_{0.02}$ alloy reached 540 cm V$^{-1}$ s$^{-1}$ [22]. The optical and electronic properties for GeSn alloys were still connected with Sn composition, substrate temperature and other growth parameters [23–25]. It is essential to make further investigations on the optoelectronic properties for GeSn alloys.

In the present, we report the structure and optoelectronic properties of compressively strained GeSn alloys. The structure of GeSn alloy films is characterized by HXRD and AFM. The refractive index is measured by SE. The carrier transport properties of GeSn films are given by Hall measurements at room temperature. The temperature dependence of Hall mobility, which depends on the Sn content, has also been investigated.

2. Experimental procedures

Compressively strained Ge$_{1-x}$Sn$_x$ films are grown by molecular-beam epitaxy at National Taiwan University. The Ge$_{1-x}$Sn$_x$ films with thickness of 30 nm are grown on the 0.02 Ω·cm Ge(004) wafer buffered by a Ge layer,
which is deposited on the substrate Ge(004). The growth temperature of the films is set to be 200 °C. Details of the films growth have been described in the previous work [26]. The structure of Ge1−xSnx films is measured by plan-view scanning electron microscope (SEM), atom force microscopy (AFM), high-resolution X-ray diffraction (HRXRD), and X-ray reflectivity (XRR). HRXRD and XRR experiments are fulfilled on the beam line BL14B1 located at Shanghai Synchrotron Radiation Facility (SSRF). The wavelength of the X-ray is chosen to be 1.238 Å. Optical constant is determined by SE(M-2000) measurements at room temperature. The angle of incidence is 60°. The wavelength ranges from 800 to 1700 nm. The Hall measurements of Ge1−xSnx/Ge/Ge films are completed in our laboratory.

3. Results and discussions

The strain of GeSn alloy films have been investigated by HRXRD [27]. The lattice mismatch between Ge and Sn induces the expansion in GeSn alloys. The in-plane compressive strain leads to out-of-plane tensile strain. The cube root value of the unit cell volume for GeSn alloy is determined by SE(M-2000) results, which is smaller than the lattice parameter calculated by Vegard law. The result indicates that these GeSn alloy films are compressively strained. The compressive strain values are estimated to be 0.29%, 0.71% and 0.83% for GeSn samples with Sn composition 0.04, 0.08, 0.14, respectively. Figures 1 and 2 show the images of AFM for Ge1−xSnx films with the Sn composition 0.08, 0.14. The surface roughness increases with the increase of Sn content, which is 0.22, 0.27 and 0.89 nm individually for Ge1−xSnx (x = 0.04, 0.08, 0.14) samples. They are smoother than that obtained by Yong-Dae Choi, et al [28].

Figure 3 displays the SEM image of the Ge0.92Sn0.08 alloy film. The surface is rough, which is consistent with the result of AFM for Ge0.92Sn0.08 alloy film. The islands can be clearly observed on the surface of Ge0.86Sn0.14 film. The slightly broad width of the X-ray rocking curve is obtained to estimate the quality of GeSn films. Typical X-ray rocking curve for GeSn with Sn composition 0.14 are shown in the inset of figure 4. The FWHM is respectively 1.32 arcsec, 1.51 arcsec and 1.57 arcsec for three samples. The slightly broad width is due to the strain in the lattice. Up to now, it is the narrowest FWHM for GeSn films with the same Sn composition in the literatures. These indicate that our films have relative high quality.

The X-ray reflectivity (XRR) may be used in checking the microstructure of the films [29, 30]. The microstructure of GeSn samples has been further investigated by XRR experiments. XRR experimental curve and the simulation pattern for Ge0.86Sn0.14 film are shown in figure 4. Parameters from the XRR simulations for all three GeSn alloy films are summarized and listed in table 1, with each parameter error about 5%. The fitted thickness for all the GeSn layers agrees with the designed one in about 10%. The mass density of GeSn layer increases with Sn composition increasing in the GeSn alloy films. Surface roughness is about 0.83 nm, 0.96 nm and 2.47 nm with x = 0.04, 0.08, 0.14 respectively for Ge1−xSnx samples. These results are consistent with surface roughness measured from AFM. The values of the mass density of GeSn films are respectively 5.34 g cm−3, 5.39 g cm−3, 5.47 g cm−3, which are all larger than that of the Ge films (5.32 g cm−3). The detailed structure of GeSn films is also characterized by B-splines, which is accurate to fit surface roughness and the thickness of films.
The fitting results of the two models are well consistent with each other. Therefore the structural parameters of films coming from XRR simulation are perfectly accurate.

The dislocation density can be deduced by the FWHMs of the symmetric and asymmetric X-ray rocking curves \([32, 33]\). Symmetric \((004)\) plane and asymmetric \((112)\) plane rocking curves of GeSn films are performed by HRXRD experiments. Figure 5 shows the symmetric and asymmetric rocking curves for Ge\(_{0.92}\)Sn\(_{0.08}\)/Ge alloy film. The FWHMs of the symmetric and asymmetric x-ray rocking curves for Ge substrate are 34.7 arcsec and 35.0 arcsec while those for epitaxial Ge\(_{0.92}\)Sn\(_{0.08}\) alloy film are 66.0 arcsec and 73.9 arcsec. The peaks of rocking curves for epitaxial Ge\(_{0.92}\)Sn\(_{0.08}\) alloy film have been broadened by the dislocation defects. The dislocation density can be estimated by the model\([33]\):

\[
D_{\text{dis}} \approx (\Delta \beta)^2/9b^2
\]

Where \(\Delta \beta\) is the changed FWHM of rocking curve due to the defects contained in epitaxial film, \(b\) is the Burger vector. These results show that the dislocation density for GeSn samples is estimated to be \(1.1 \times 10^7/\text{cm}^2\), \(1.3 \times 10^7/\text{cm}^2\), \(1.1 \times 10^8/\text{cm}^2\), respectively. The increase of surface roughness, mass density and dislocation density may be induced by the increase of Sn composition and strain in GeSn films.

Figure 6 shows the real part of refractive index for GeSn alloys in the NIR range from 800 to 1700 nm by SE measurements. The results show that the value of refractive index adheres to a function with the wavelength for Ge substrate and GeSn samples. The refractive index of GeSn samples has the similar behavior as that of the

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**Figure 2.** Images of AFM for Ge\(_{0.90}\)Sn\(_{0.10}\) film and the root mean square of surface roughness is 0.89 nm. Islands occur on the surface of the film. (a) Two-dimensional image for Ge\(_{0.90}\)Sn\(_{0.10}\) film. (b) Three-dimensional image for Ge\(_{0.90}\)Sn\(_{0.10}\) film.

**Figure 3.** A SEM morphology of the surface for Ge\(_{0.86}\)Sn\(_{0.14}\) film. The image shows that the surface of the sample is rough.
substrate Ge film. But the refractive index of Ge is smaller than that of GeSn samples. Researches have shown that the refractive index of films is related to variations in strain, the density of films \[3, 6\]. The surface roughness and mass density for GeSn samples have been discussed above. Sn-induced strain brings about higher surface roughness and mass density for GeSn samples. For Ge\(_{0.086}\)Sn\(_{0.14}\) sample, the surface roughness and mass density are much larger than other two samples with Sn composition 0.04, 0.08. The refractive index of three GeSn samples has the similar behavior. For another IV–IV compounds, GeSi films have been also investigated by SE \[10\]. The refractive index of GeSi in the range 900–1700 nm varies from 3.4 to 3.8, which is lower than that of Ge wafer. The higher refractive index of films may mainly result from the higher surface roughness and mass density.

| Table 1. Structural parameters for three GeSn samples, including surface roughness, thickness and mass density. |
|---------------------------------------------------------------|
| **Sn composition** | **Surface roughness/nm** | **Thickness/nm** | **Mass density (g cm\(^{-3}\))** |
|-------------------|--------------------------|----------------|-----------------------------|
| 4%                | 0.81                     | 34.39          | 0.85                        |
|                   |                          |                | 33.69                       |
|                   |                          |                | 5.34                        |
| 8%                | 0.97                     | 33.00          | 0.96                        |
|                   |                          |                | 33.50                       |
|                   |                          |                | 5.39                        |
| 14%               | 2.50                     | 31.53          | 2.44                        |
|                   |                          |                | 31.86                       |
|                   |                          |                | 5.47                        |

Figure 4. Experimental curve and fitting curve of XRR for Ge\(_{1-x}\)Sn\(_x\) film with \(x = 0.14\) is described. The inset shows the X-ray rocking curve from the (004) diffraction of Ge\(_{0.86}\)Sn\(_{0.14}\) film. The FWHM of the peak is 1.57 arcsec.

Figure 5. Symmetric and asymmetric rocking curves are showed for Ge\(_{1-x}\)Sn\(_x\) (\(x = 0.08\)) epitaxial film and Ge substrate. (a) Symmetric (004) X-ray rocking curves for Ge\(_{0.86}\)Sn\(_{0.14}\)/Ge alloy film. (b) Asymmetric (112) X-ray rocking curves for Ge\(_{0.86}\)Sn\(_{0.14}\)/Ge alloy film.
of GeSn alloys. This indicates that the refractive index of GeSn samples relates to the surface roughness and mass density of the alloys in the NIR range.

Figure 7 shows the Sn-dependent refractive index for GeSn films at wavelengths 800, 1000, and 1300 nm. A second-order polynomial function can be used to fit the values of refractive index for GeSn alloy films. Similar method has been taken to describe the refractive index of GeSi, another alloy in column IV [10]. The function can be expressed as $n(x, \lambda) = n_{Ge}(\lambda) + b(\lambda)x + c(\lambda)x^2$, where $n_{Ge}(\lambda)$ is the refractive index of substrate Ge at specific wavelength, $b(\lambda)$, and $c(\lambda)$ depend on the wavelength. Therefore, the refractive index of GeSn samples may be estimated by the empirical expression $n(x, \lambda) = n_{Ge}(\lambda) + (-2 + 3.5\lambda)x + 5(1 - \lambda)x^2$, with the wavelength in the range 800–1700 nm, which cover the telecommunications wavelength of $\lambda = 1.31$ um, 1.55um. Then the compounds of GeSi and GeSn all can be fitted by polynomial function with second-order. According to the formula $\alpha = 4\pi k/\lambda$, the absorption coefficient of Ge$_{1-x}$Sn$_x$ sample can be calculated. Here k is the extinction coefficient, which may be obtained from the refractive of index measurement. Table 2 shows the extinction coefficients and absorption coefficients for GeSn alloy films at wavelengths 1.31 and 1.55um. At certain wavelength, the extinction coefficients increase with the increase of Sn composition for GeSn samples. Reference [34] studied that the absorption coefficient $\alpha_{Ge}(1.55um)$ is 625 cm$^{-1}$, while the absorption coefficients $\alpha_{GeSn}(1.55um)$ are 32000 cm$^{-1}$, 39000 cm$^{-1}$, 47000 cm$^{-1}$ for GeSn samples with Sn composition 0.04, 0.08 and 0.14, respectively. Figure 8 shows the absorption coefficients for Ge$_{1-x}$Sn$_x$ samples. The absorption coefficients have been plotted as a function of photon energy. In the near infrared wavelength range,

Figure 6. Wavelength dependence of the refractive index for compressively strained Ge$_{1-x}$Sn$_x$ films with Sn fraction 0.04, 0.08, 0.14 and the substrate Ge.

Figure 7. The refractive index of GeSn samples is shown at wavelength 0.8 um, 1.0 um and 1.3 um.
the absorption coefficient can be increased by adding Sn content for compressively strained Ge\(_{1-x}\)Sn\(_x\) samples, which is useful for the design of near infrared optical detectors.

Hall measurements are carried out to investigate the electronic properties of GeSn films. The behaviors of carrier mobility and concentration of GeSn alloys grown on Ge are studied at room temperature. Table 3 shows the Hall coefficient, carrier concentration and carrier mobility for GeSn samples. The n-type semiconducting GeSn films are determined by negative Hall coefficients. The carrier concentration of GeSn films increases with the Sn composition increasing, which is smaller than that of Ge layer. This result shows that the defects measured by HRXRD lead to the decrease of donor levels. The Hall electron mobility of Ge\(_{0.96}\)Sn\(_{0.04}\) samples is larger than that of Ge layer. And the mobility decreases while Sn composition increases. The Hall electron mobility for Ge\(_{0.96}\)Sn\(_{0.04}\)/Ge film is higher than that of Ge\(_{0.86}\)Sn\(_{0.14}\)/Ge film by 20.2%. This indicates that Sn composition induces the high Hall electron mobility in GeSn film and defects or roughness in films degrades the carrier mobility. The electron mobility appears maximum value at Sn composition 0.04, which is slightly above the solubility of Sn in Ge. The result is consistent with the conclusion of GeSn semiconductor in the literatures [20, 21]. Figure 9 shows that the Hall mobility is negative dependent on the carrier concentration, which identifies nonlinear. P-type GeSn alloys show the similar nonlinear behavior [24]. And the carrier concentration dependence of electronic mobility for bulk Ge shows linear behavior in the reference. This shows that the carrier mobility of GeSn samples may be decreased by strain-induced defects contained in the films.

**Figure 8.** Absorption coefficients are obtained for GeSn samples at Sn content 0.04, 0.08 and 0.14.

**Table 2.** The absorption coefficient, extinction coefficient for Ge\(_{1-x}\)Sn\(_x\)/Ge samples.

| Absorbance wavelength | 1.31 \(\mu\)m | 1.55 \(\mu\)m |
|-----------------------|----------------|----------------|
| Sn composition       | 0.04 0.08 0.14 | 0.04 0.08 0.14 |
| Extinction coefficient| 0.52 0.62 0.81 | 0.39 0.47 0.67 |
| Absorption coefficient\((\times 10^5 \text{cm}^{-1})\) | 0.50 0.59 0.70 | 0.32 0.39 0.47 |

**Table 3.** The Hall coefficient, carrier concentration and carrier mobility for Ge\(_{1-x}\)Sn\(_x\)/Ge samples at 300 k.

| Sn composition | \(x = 0\) | \(x = 0.04\) | \(x = 0.08\) | \(x = 0.14\) |
|----------------|----------|----------|----------|----------|
| Hall coefficient | -21 | -31 | -23 | -22 |
| carrier concentration\((\text{cm}^{-3})\) | \(5.8 \times 10^{17}\) | \(3.91 \times 10^{17}\) | \(5.20 \times 10^{17}\) | \(5.39 \times 10^{17}\) |
| carrier mobility\((\text{cm}^2\text{V}^{-1}\text{s}^{-1})\) | 1133 | 1210 | 1123 | 1007 |
The Hall mobility can be written by Matthiessen’s rule for GeSn films as following [22]:

\[
\frac{1}{\mu} = \frac{1}{\mu_{\text{imp}}} + \frac{1}{\mu_{\text{phonon}}} + \frac{1}{\mu_{\text{others}}}
\]

Here \( \mu_{\text{imp}} \) \( \mu_{\text{phonon}} \) refer to impurity, phonon scatterings, \( \mu_{\text{others}} \) is related to surface/interface roughness, alloy, and grain boundary scatterings. For Ge doped semiconductor, temperature dependence of \( \mu_{\text{others}} \) can be

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**Figure 9.** Reduced Hall mobility depends on the carrier concentration for GeSn samples.

**Figure 10.** Temperature dependences of carrier mobility for GeSn/Ge films. (a) The electronic Hall mobility for Ge\(_{0.96}\)Sn\(_{0.04}\)/Ge film. The inset shows that the resistivity for Ge\(_{0.96}\)Sn\(_{0.04}\)/Ge film varies from low temperature to room temperature. (b) The electronic Hall mobility for Ge\(_{0.86}\)Sn\(_{0.14}\)/Ge film.
neglected compared to $\mu_{\text{imp}}$, $\mu_{\text{phonon}}$ [24]. As the temperature changed, $\mu_{\text{imp}}$ is related to $T^{-1/2}$ and $\mu_{\text{phonon}}$ is related to $T^{-3/2}$. Figure 10 shows the temperature dependence of Hall mobility for Ge$_{0.96}$Sn$_{0.04}$/Ge and Ge$_{0.86}$Sn$_{0.14}$/Ge film alloys. With the temperature increasing, the Hall electronic mobility increases at lower temperature and has negative tendency at higher temperature. This indicates that impurity scattering is dominant at lower temperature, while phonon scattering is more dominant than impurity scattering at higher temperature. The Hall mobility of Ge$_{0.96}$Sn$_{0.04}$/Ge film is higher than that of Ge$_{0.86}$Sn$_{0.14}$/Ge film at all temperature point. This trend is consistent with that of the room temperature. This behavior is due to the fact that the strain-induced defects cause alloy scattering mentioned above. Figure 10(a) shows that the Hall electronic mobility reached to maximum value 2082 cm$^2$/Vs at $T = 122$ K for Ge$_{0.96}$Sn$_{0.04}$. The inset of figure 10(a) indicates that the resistivity of Ge$_{0.96}$Sn$_{0.04}$/Ge film. The resistivity of the Ge$_{0.96}$Sn$_{0.04}$/Ge film exceeds that of Ge(004) wafer, which is 0.02 $\Omega$·cm. The temperature dependence of the resistivity for Ge$_{0.96}$Sn$_{0.04}$/Ge film shows the same scattering with the result of temperature dependence of the carrier mobility. As shown in figure 10(b), for Ge$_{0.86}$Sn$_{0.14}$, the maximum electronic mobility is up to 1396 cm$^2$/Vs at $T = 178$ K. The maximal electronic mobility of Ge$_{0.96}$Sn$_{0.04}$/Ge film is higher than that of Ge$_{0.86}$Sn$_{0.14}$/Ge film by 49.1%, which is larger than the mobility variation 20.2% above at room temperature. The conclusion reveals that temperature dependence of strain may reduce the hall electronic mobility. Transitional temperature varies from 122 K to 178 K. The reason for the transitional point is clearly that Sn induced larger peak temperature for the sample Ge$_{0.86}$Sn$_{0.14}$ compared to the sample Ge$_{0.86}$Sn$_{0.04}$. The result indicates that Sn composition is critical for the transition of the temperature-dependent Hall mobility.

4. Conclusion

Compressively strained GeSn alloy films have been obtained with Sn composition 0.04, 0.08 and 0.14. The structure has been investigated by SEM, AFM and HRXRD. Then the optical and electrical properties of GeSn alloy films have been measured by SE and Hall measurement. The surface roughness and mass density for GeSn samples may responsible for the value of refractive index. In NIR range, the dispersion relationship for GeSn samples can be expressed as the Second order polynomial function $n(x, \lambda) = n_0(\lambda) + (2 + 3.5\lambda)x + 5(1 - \lambda)x^2$. The Hall measurement shows the reduced hall mobility related to the dislocation density for GeSn/Ge alloy films. Temperature dependence of the Hall mobility indicates that the maximal electronic mobility is up to 2082 cm$^2$/Vs at 122 K with Sn composition 0.04.

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References

[1] Du W et al 2014 Appl. Phys. Lett. 104 241110
[2] Chang C, Li H, Huang S H, Cheng H H, Sun G and Soref R A 2016 Appl. Phys. Lett. 108 151101
[3] Natali F, Semond F, Massies I, Byrne D, Laugt S, Tottereau O, Vennegues P, Dogheche E and Dumont E 2003 Appl. Phys. Lett. 82 1386
[4] Lieten R R, Decoster S, Vanromme A, Peters S, Bastillo K C, Haller E E, Menghini M and Locquet J P 2013 Appl. Phys. Lett. 102 032106
[5] Nikolenko A S, Strelchuk V V, Safriuk N V, Kryvyi S B, Kladko V P, Oberemok O S, Borkowska LV and Sadofyev Y G 2016 Appl. Phys. Lett. 108 161110
[6] Tsang W S, Chen K Y, Mak C L and Wong K H 2003 Appl. Phys. Lett. 83 1599
[7] Serna R, de Sand J C G, Ballesteros J M and Afonso C N 1998 J. Appl. Phys. 84 4509
[8] Sadot T, Kai Y, Matsumura R, Moto K and Miyao M 2016 Appl. Phys. Lett. 109 232106
[9] Pickering C and Carlone R T 1994 J. Appl. Phys. 75 4642
[10] De Sande J C G, Rodriguez A and Rodriguez T 1995 Appl. Phys. Lett. 67 3402
[11] Romano L, Napolitani E, Privitera V, Scala S, Terrasi A, Mirabella S and Grimaldi M G 2003 Materials Science and Engineering B102 69
[12] Chen Y C, Li S H, Bhattacharya P K, Singh J and Hinckley J M 1994 Appl. Phys. Lett. 64 3110
[13] Gujik M, Lechner R, Buschbeck M and Stutzmann M 2005 Appl. Phys. Lett. 86 062115
[14] Cook C S, Zollner S, Bauer M R, Aella P, Kouvetakis J and Menendez J 2004 Thin Solid Films 455–456 217–21
[15] D’Costa V R, Cook C S, Birdwell A G, Littler C L, Canonicino M, Zollner S, Kouvetakis J and Menendez J 2006 Phys. Rev. B 73 125207
[16] Vincent B et al 2011 Appl. Phys. Lett. 99 152103
[17] Mukhopadhyay B, Sen G, Basu R, Mukhopadhyay S and Basu P K 2017 Phys. Status Solidi b 254 1700244
[18] Yoshikawa I, Kurosawa M, Takeuchi W, Sakashita M, Nakatsuka O and Zaima S 2017 Mater. Sci. Semicond. Process. 70 151
[19] Chen N L, Lin G, Zhang L, Li C, Chen S Y, Huang W, Xu J F and Wang J Y 2017 Jpn. J. Appl. Phys. 56 050301
[20] Taoka N, Capellini G, Schlykow V, Montanari M, Zaima S and Schroeder T 2017 Mater. Sci. Semicond. Process. 70 139
[21] Moto K, Yoshimine R, Suemasu T and Toko K 2018 Sci. Rep. 8 14832
[22] Moto K, Saitoh N, Yoshizawa N, Suemasu T and Toko K 2019 Appl. Phys. Lett. 114 112110
[23] Han D, Ye H, Song Y X, Zhu Z Y S, Yang Y K, Yu Z Y, Liu Y M, Wang S M and Di Z F 2019 Appl. Surf. Sci. 463 581
[24] Nakatsuka O, Tsutsui N, Shimura Y, Takeuchi S, Sakai A and Zaima S 2010 Jpn. J. Appl. Phys. 49 04DA10
[25] Lin Y J, Tsao H Y and Liu D S 2012 Appl. Phys. Lett. 101 013302
[26] Yu I S, Wu T H, Wu K Y, Cheng H H, Mashanov V I, Nikiforov A I, Pchelyakov O P and Wu X S 2011 AIP Adv. 1 012118
[27] Tao P, Huang L, Cheng H H, Wang H H and Wu X S 2014 Chin. Phys. B 23 088112
[28] Kil Y H, Kang S, Jeong T S, Shim K H, Kim D J, Choi Y D, Kim M J and Kim T S 2018 J. Korean Phys. Soc. 9 1063
[29] Zhang A M et al 2005 Appl. Phys. A 81 501
[30] Zhang A M, Chen Z X, Zou W Q, Lv B, Ge J J, Cai H L, Du J, Wu X S, Zhang S J and Zhou S M 2012 J. Appl. Phys. 111 07A704
[31] Weber J W, Hansen T A R, van de Sanden M C M and Engeln R 2009 J. Appl. Phys. 106 123503
[32] Heying B, Wu X H, Keller S, Li Y, Kapolnek D, Keller B P, Denkena S P and Speck J S 1996 Appl. Phys. Lett. 68 643
[33] Zhai Z Y, Wu X S, Cai H L, Lu X M, Hao J H, Gao J, Tan W S, Jiao Q J, Wang H H and Wang Y Z 2009 J. Phys. D 42 105307
[34] D’Costa V R, Fang Y Y, Mathews J, Roucka R, Tolle J, Menendez J and Kouvetakis J 2009 Semicond. Sci. Technol. 24 115006