Femtosecond laser irradiation-induced infrared absorption on silicon surfaces

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The near-infrared (NIR) absorption below band gap energy of crystalline silicon is significantly increased after the silicon is irradiated with femtosecond laser pulses at a simple experimental condition. The absorption increase in the NIR range primarily depends on the femtosecond laser pulse energy, pulse number, and pulse duration. The Raman spectroscopy analysis shows that after the laser irradiation, the silicon surface consists of silicon nanostructure and amorphous silicon. The femtosecond laser irradiation leads to the formation of a composite of nanocrystalline, amorphous, and the crystal silicon substrate surface with microstructures. The composite has an optical absorption enhancement at visible wavelengths as well as at NIR wavelength. The composite may be useful for an NIR detector, for example, for gas sensing because of its large surface area.

Keywords: near-infrared absorption; nanostructured silicon; amorphous silicon

1. Introduction

Silicon has formed an immense global industry – it has a large variety of applications in optoelectronics. However, the large band gap of silicon solid restricts its applications in making optoelectronic devices for utilizing infrared (IR) light [1–6]. If its wavelength is longer than 1.1 μm, i.e., its photon energy is less than the silicon band gap energy (1.1 eV), the light cannot be absorbed as it passes through silicon solid because the photon energy is not large enough to excite an electron to the conduction band from the valence band of the silicon solid. To improve the optical properties of silicon, femtosecond laser irradiation method has been applied to treat silicon surfaces [3,7–10]. In order to increase the silicon absorption in the IR range, the microstructured silicon was formed with femtosecond laser irradiation on silicon surfaces in the presence of the background gas of SF₆. After sulfur atoms were doped into the silicon surface, the band gap of silicon was filled with the sulfur impurity energy states. As a result, the absorption for IR light with photon energy less than 1.1 eV can be obtained [3,7]. The IR absorption has potential applications for the IR optoelectronic devices, such as IR image detector.

Here we report that the IR absorption of silicon can be directly obtained through fabricating a silicon substrate surface with a femtosecond laser irradiation in air without applying any special background gas [11–13]. The scanning electron microscope (SEM)
images of the fabricated silicon surface have shown arrays of silicon hills in micrometers with smaller nano-scaled structures on the hills’ surfaces, which were generated during the laser irradiation. The phonon Raman spectroscopy analysis of the fabricated surface has shown that amorphous silicon as well as silicon nano-crystalline was generated on the silicon surface. The IR optical absorption was largely increased after being processed by the irradiation of femtosecond laser. This absorption depends on several laser-processing parameters such as laser pulse duration, pulse number, and pulse energy. The increment of the IR absorption is originated from the composite of nano-crystalline silicon and amorphous silicon on the silicon substrate surface because amorphous silicon provides electronic energy states in the energy band gap for the IR absorption [14].

On the one hand, amorphous silicon-related papers of laser irradiation mainly concentrated on the application of the laser-annealing effect, i.e., amorphous silicon became silicon crystalline or micro/nanostructured silicon for better optoelectronics applications [15–26]. On the other hand, amorphous silicon and lattice distortions could be formed with the femtosecond laser irradiation [27–31]. The formed amorphous silicon was analyzed with different techniques including transmission electron microscopy, energy dispersive X-ray analysis [27], non-destructive optical imaging method of scanning laser microscopy [28], and phonon Raman spectroscopy [29,30]. However, the thickness of the formed amorphous silicon layer was found to be only tens of nanometers, and its IR optical property has not been noticed and studied because the amount of the amorphous silicon was too small to influence the optical properties of the silicon substrate. In the present work, we have transformed silicon solid smooth surface into a composite of nanocrystalline silicon and amorphous silicon on the silicon solid surface with microstructures using a simple femtosecond laser irradiation in air. We found that the microstructures enhanced the optical absorptions and the amount of the formed amorphous silicon was large enough to considerably influence the IR optical absorption of the irradiated silicon substrates. The composite will be useful for manufacturing silicon-related IR optoelectronic device, such as IR sensors and solar cells.

2. Experimental
A clean silicon wafer (p-Si (100), thickness of 500 μm, resistivity of 20 Ω·m) was placed on the translation stage and was irradiated in air by a 1 kHz train of 35 fs, 6 mJ pulses at 800 nm wavelength from an amplified Ti:sapphire laser system with the incident laser beam perpendicular to the wafer surface. The sample was scanned line by line with the distance of 150 μm between two lines at even speed to make the silicon receive uniform exposure to the laser in an area of 1 cm × 1 cm. Laser beam splitters are used to control the average laser fluence. The pulse duration was controlled by adjusting the laser compressor and measured by an autocorrelator around the sample surface location between a lens and its focal point. The sample translation velocity in the direction perpendicular to the laser beam direction was used to control the average pulse number irradiated on the substrate surface. The average pulse number n was calculated by applying the formula \( n = \frac{wf}{v} \), where w is the full width at half maximum (FWHM) of the Gaussian laser beam profile on the sample surface, f is the frequency of the laser pulse train, and v is the sample translation velocity [12]. In this work, w was 100 μm, f was 1000, and v varied from 0.3 mm/s to 2.5 mm/s. After the laser irradiation, the silicon wafer was cleaned by distilled water ultrasonically to remove the silicon dust sprayed out during the laser treatment procedure and then further washed with 10% hydrofluoric acid to remove the silicon oxide layer formed.
during the laser ablation procedure. The cleaning procedure can eliminate the effect of silicon dust and silicon oxide layer during Raman spectrum test and optical absorptance measurement.

The crystallinity of the sample at room temperature was analyzed with a Raman spectrometer (Optic Senterra, Bruker). A continuous wave laser at the wavelength of 532 nm was used as the excitation source for the Raman spectroscopy measurement. The sample surface structure was also studied by using an SEM (JEOL 7401F). The optical property of the sample was studied with a spectrophotometer (U-4001, HITACHI) equipped with a precise integrating sphere. The reflectance ($R$) and transmittance ($T$) were measured with the integrating sphere. The absorptance ($A$) of the sample was then obtained with the formula $A = 1 - T - R$.

3. Experimental results and discussion

Raman spectroscopy analysis is an effective method to study the silicon surface irradiated by femtosecond laser [29,30]. Figure 1 shows the Raman spectrum of the c-Si after the femtosecond laser irradiation. In the experiment to prepare the sample, the laser pulse duration was 35 fs, the average laser fluence was 6 kJ/m$^2$, and the pulse number was 250. Figure 1(a) shows the comparison of Raman spectrum of laser processed Si with that of Si crystal. The Raman main peak of silicon crystal is at 520.0 cm$^{-1}$, while the main peak of the laser-irradiated silicon has shifted to lower energy from 520.0 cm$^{-1}$ to 513.5 cm$^{-1}$ with an asymmetry broadening. Because of the phonon confinement effect, the redshift and the asymmetric broadening of the one phonon Raman signal at 520 cm$^{-1}$ have been used to estimate the average size of small silicon crystals [23,32]. The redshift and the asymmetry broadening of the Raman peak around 520.0 cm$^{-1}$ indicate that silicon nanocrystals were generated during the laser irradiation. The Raman spectrum suggests that the average size of the generated silicon nanocrystals was around 10 nm [33] although the spectrum cannot give the shapes and the size distribution of the silicon nanocrystals. Figure 1(b) shows the Raman spectrum of weak signals from wavenumber of 100 cm$^{-1}$ to 900 cm$^{-1}$. The broad shoulder near the nanocrystal Si peak of 513.5 cm$^{-1}$ can be observed. As shown in Figure 1(b), we have deconvoluted the spectrum to obtain the peak centered at a wavenumber of 513.5 cm$^{-1}$ which belongs to the nanocrystal Si, and four broad peaks which are the characteristic peaks of amorphous silicon at wavenumber of 480 cm$^{-1}$ (transverse optical mode), 380 cm$^{-1}$ (longitudinal optical mode), 301 cm$^{-1}$ (longitudinal acoustic mode), and 150 cm$^{-1}$ (transverse acoustic mode) [34–39]. The Raman spectrum analysis has revealed that nanostructured silicon and amorphous silicon were generated simultaneously during the laser irradiation.

Figure 2 shows the Si surface SEM images after laser irradiation. Figure 2(a) shows that the structures formed on the silicon surface after the femtosecond laser irradiation are arrays of silicon micro-hills. The micro-hills were formed because of the line-by-line laser scanning. The cross section of each one of the hills is in isosceles triangle-like shape. The bottom side of the triangle is about 80-micrometer long. The height of the triangle is about 100 micrometers. Figure 2(b) shows the silicon micro-hill feature viewed after rotating the substrate at 90° and titling at 45° to the surface normal. Figure 2(c) and 2(d) shows that on the surface of silicon micro-hills, there are smaller structures generated during the laser irradiation process. Figure 2(e) and 2(f) shows the SEM image with larger magnification at different locations of the hills; the images show the same nanostructures or submicrostructures at different locations of the surface of the micro-hill surfaces. The laser wavelength was 532 nm for the excitation source for the
Raman spectroscopy measurement. The laser penetration depth, $\lambda/4\pi\kappa$ (where $\lambda$ and $\kappa$ are the wavelength and the imaginary part of the complex refractive index of silicon, respectively [40]), is less than 2 $\mu$m that is much smaller than the surface structures shown in the images of Figure 2(e) and 2(f). The Raman signals of the sample were from the nanocrystals and amorphous silicon but not from the silicon crystal microstructures beneath the nanocrystals and amorphous silicon. Therefore, we have transformed the crystal silicon into a composite of nanocrystalline, amorphous, and crystal silicon substrate surface with micro-morphologies.

Figure 3 shows the optical absorptance of a laser-irradiated silicon sample between 380 and 2000 nm. The experimental condition used was 35 fs pulse duration, 6 kJ/m$^2$ average pulse fluence, and 250 laser pulses. The absorptance of regular silicon is also shown in Figure 3 for comparison with the laser-irradiated Si sample. As wavelength
increases, the absorptance of the sample decreases. The absorption is almost a linear function of wavelength between 400 nm and 2000 nm. The comparison indicates that the structured silicon’s optical absorptance is much higher than that of the regular silicon in the measured wavelength range. The absorptance at wavelength of 1.5 µm of the structured silicon is about 50% that is much higher than that of unstructured silicon substrate. In visible wavelengths part, the absorptance increment is mainly originated from the effect of multiple reflections, i.e., the incident light is reflected multiple times on the micro/nanostructured surface and is absorbed by the silicon [7–11]. In near-infrared (NIR) region, there is an obvious drop in wavelength around 1.1 µm for the unstructured silicon
The absorptance curve, which is corresponding to the silicon band gap. The light with wavelength longer than 1.1 µm does not have enough photon energy to excite electron from the valence band to the conduction band of silicon solid. As a result, silicon is almost transparent to the light in this range. However, the silicon after laser irradiation has a large IR optical absorptance because the disordered amorphous silicon does not have a defined band gap.

Figure 4 shows laser pulse duration effect on the IR absorptance when keeping the pulse number as 250 and the average pulse fluence as 6 kJ/m². As the pulse duration decreased from 100 to 35 fs, the IR absorptance increased in the NIR range although changing the pulse duration did not make a large difference. The IR absorptance change was less than 0.1 or 10%. Meanwhile, the disappeared band gap when the pulse duration

Figure 3. The optical absorption comparison of the femtosecond laser irradiated sample A with crystalline silicon. The silicon substrate has been irradiated with laser with pulse duration of 35 fs, an average laser fluence of 6 kJ/m², and a pulse number of 250.

Figure 4. The optical absorptance of silicon after laser irradiation at two different laser pulse durations, 35 fs and 100 fs. The average laser fluence and pulse number are 6 kJ/m² and 250, respectively.
was 35 fs around 1.1 μm was observable when the pulse duration was adjusted to 100 fs. When irradiating with longer pulse duration, we got less amorphous silicon, and thus less IR absorptance.

Figure 5 shows the laser pulse number dependence of the optical absorptance while keeping the average laser fluence as 6 kJ/m² and the pulse duration as 35 fs. When the pulse number increased from 40 to 250, the absorptance changed less than 10% for the wavelength less than 1000 nm, but increased significantly between 1000 and 2000 nm. For the small pulse number, the optical absorptance approached to that of unstructured silicon, i.e., although a small number of femtosecond pulse irradiation changed the surface structures, there was not enough amorphous silicon to change in the NIR optical property of the silicon substrate as a whole system. When the pulse number is 250, NIR absorptance reached the maximum. As the pulse number was larger than 250, the induced NIR absorptance became smaller, which will be further analyzed in the following text.

Figure 6 shows the laser fluence dependence of optical absorptance when keeping the pulse number as 250 laser pulses and the pulse duration as 35 fs. For the wavelength between 1250 and 2000 nm, the absorptance increases as the laser fluence increases. For the case of average laser fluence of 1.5 and 0.7 kJ/m², the characteristic Si band gap can still be observed around the wavelength of 1.1 μm. While as the fluence increases to 6 kJ/m², the band gap cannot be found on the absorptance spectrum. However, we also found that when the fluence became stronger than 6 kJ/m², the NIR absorptance became smaller and similar to that of Si irradiated with lower laser fluences as shown in Figure 6 for the fluence of 7 kJ/m². This is opposite to the fluence dependence of optical absorptance when the fluence was weaker than 6 kJ/m².

In Figure 7(a), we compare Sample A in Figures 1 and 3 with the samples with more irradiation, i.e., more accumulated irradiation energy absorbed by the substrate. Sample B was made with the irradiation of the laser 35 fs pulse duration, fluence of 7 kJ/m², and 250 laser pulses; and Sample C at 35 fs pulse duration, fluence of 6 kJ/m², and 300 laser pulses. Figure 7(b) shows the corresponding Raman spectra of Samples A, B, and C. From the Raman spectra, we know that the crystalline peak position of Sample A was at
513.5 cm\(^{-1}\), Sample B at 516.0 cm\(^{-1}\), and Sample C at 518.0 cm\(^{-1}\). The amorphous broad band at 480 cm\(^{-1}\) in Samples B and C became weak relative to the crystalline peak in comparison with that in Sample A. Thus, the amorphous silicon became crystalline silicon when more laser energy was irradiated on the amorphous silicon, and the IR absorbance decreased as shown in Figure 7(a). Therefore, as the pulse number or pulse energy increases, the NIR absorbance decreases after reaching a maximum value. The silicon amorphous structure goes back to silicon crystalline structure under the influence of laser irradiation \cite{15-26}. The silicon structure can be changed back and forth between crystalline and amorphous by controlling the experimental conditions.

The Raman spectrum of the silicon after the laser irradiation shows that the crystalline silicon can change to amorphous silicon under the effect of laser irradiation. From the obvious IR absorption, we know that there is a significant amount of amorphous silicon formed. The sharp and redshifted main Raman peak indicates that some of the silicon in the surface is in the form of nanocrystalline. The silicon atoms of a nanocrystalline surface are usually in a deformed lattice that is different from that in the bulk. The surface atoms can easily join with the surrounding amorphous silicon. The amorphous silicon fills in the space surrounding silicon nanocrystals and the crystal silicon substrate surface with microstructures. This forms a composite that absorbs NIR light significantly. The composite may be useful for an NIR detector, for example, for gas sensing because of the enhancement in its surface area.

4. Summary
The femtosecond laser irradiation on silicon solid leads to the formation of a composite of nanocrystalline, amorphous, and silicon substrate surface with microstructures. The composite has an optical absorption enhancement both at the visible wavelengths and NIR wavelengths. The transformations between crystalline silicon and amorphous silicon with the femtosecond pulse laser irradiation may provide a new method to make low cost IR detectors with silicon.
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Disclosure statement

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Figure 7. The radiation effect on the silicon. Sample A is made with the irradiation of the laser 35 fs pulse duration, fluence of 6 kJ/m², and 250 laser pulses; Sample B at 35 fs pulse duration, fluence of 7 kJ/m², and 250 laser pulses; and sample C at 35 fs pulse duration, fluence of 6 kJ/m², and 300 laser pulses. (a) The optical absorptance of silicon after different laser irradiations. (b) The Raman spectra of silicon samples after different laser irradiations.
References

[1] H. Sai, Y. Kanamori, and M. Kondo, Flattened light-scattering substrate in thin film silicon solar cells for improved infrared response, Appl. Phys. Lett. 98 (2011), pp. 113502.

[2] D.E. Carlson and C.R. Wronski, Amorphous silicon solar cell, Appl. Phys. Lett. 28 (1976), pp. 671.

[3] J.E. Carey, C.H. Crouch, M. Shen, and E. Mazur, Visible and near-infrared responsivity of femtosecond-laser microstructured silicon photodiodes, Opt. Lett. 30 (2005), pp. 14.

[4] H. Zhou, G. Fang, L. Yuan, C. Wang, X. Yang, H. Huang, and X. Zhao, Deep ultraviolet and near infrared photodiode based on n-ZnO/p-silicon nanowire heterojunction fabricated at low temperature, Appl. Phys. Lett. 94 (2009), pp. 1.

[5] H. Zogg, A. Fach, J. John, J. Masek, P. Mueller, C. Paglino, and S. Blunier, Photovoltaic IV-VI on Si infrared sensor arrays for thermal imaging, Opt. Eng. 34 (1995), pp. 1964.

[6] H. Zogg, C. Maisen, J. Masek, and S. Blunier, Photovoltaic lead-chalcogenide on silicon infrared sensor arrays, Opt. Eng. 33 (1994), pp. 1440.

[7] T.H. Her, R.J. Finlay, C. Wu, S. Deliwala, and E. Mazur, Microstructuring of silicon with femtosecond laser pulses, Appl. Phys. Lett. 73 (1998), pp. 1673.

[8] A.J. Pedraza, J.D. Fowlkes, and D.H. Lowndes, Surface nanostructuring of silicon, Appl. Phys. Lett. 77 (2000), pp. 3018.

[9] M.Y. Shen, C.H. Crouch, J.E. Carey, and E. Mazur, Femtosecond laser-induced formation of submicrometer spikes on silicon in water, Appl. Phys. Lett. 85 (2004), pp. 5694.

[10] M. Shen, J.E. Carey, C.H. Crouch, M. Kandyla, H.A. Stone, and E. Mazur, High-density regular arrays of nanometer-scale rods formed on silicon surfaces via femtosecond laser irradiation in water, Nano. Lett. 8 (2008), pp. 2087–2091. doi: 10.1021/nl80291q

[11] T.-H. Her, R.J. Finlay, C. Wu, and E. Mazur, Femtosecond laser-induced formation of spikes on silicon, Appl. Phys. A. 70 (2000), pp. 383–385. doi: 10.1007/s003390051052

[12] C.H. Crouch, J.E. Carey, M. Shen, E. Mazur, and F.Y. Genin, Infrared absorption by sulfur-doped silicon formed by femtosecond laser irradiation, Appl. Phys. A. 79 (2004), pp. 1635. doi: 10.1007/s00339-004-2676-0.

[13] C. Wu, C.H. Crouch, L. Zhao, J.E. Carey, R. Younkin, J.A. Levinson, E. Mazur, R.M. Farrell, P. Gothoskar, and A. Karger, Near-unity below-band-gap absorption by microstructured silicon, Appl. Phys. Lett. 78 (2001), pp. 13.

[14] J. Zhu, Z. Yu, G.F. Burkhard, C. Hsu, S.T. Connor, Y. Xu, Q. Wang, M. McGehee, S. Fan, and Y. Cui, Optical absorption enhancement in amorphous silicon nanowire and nanocore arrays, Nano Lett. 9 (2009), pp. 279–282. doi: 10.1021/nl802886y

[15] J.-M. Shieh, Z.-H. Chen, B.-T. Dai, Y.-C. Wang, A. Zaitsev, and C.-L. Pan, Near-infrared femtosecond laser-induced crystallization of amorphous silicon, Appl. Phys. Lett. 85 (2004), pp. 1232.

[16] G.J. Lee, S.H. Song, Y.P. Lee, H. Cheong, C.S. Yoon, Y.D. Son, and J. Jang, Arbitrary surface structuring of amorphous silicon films based on femtosecond-laser-induced crystallization, Appl. Phys. Lett. 89 (2006), pp. 151907.

[17] M.-J. Sher, K. Hammond, L. Christakis, and E. Mazur, The photovoltaic potential of femtosecond-laser textured amorphous silicon, Laser-based Micro- and Nanopackaging and Assembly VII, Proc. SPIE. 8608 (2013), pp. 86080R.

[18] A. Gat, J.F. Gibbons, T.J. Magee, J. Peng, V.R. Deline, P. Williams, and C.A. Evans Jr, Physical and electrical properties of laser-annealed ion-implanted silicon, Appl. Phys. Lett. 32 (1978), pp. 276.

[19] A. Gat, L. Gerzberg, J.F. Gibbons, T.J. Magee, J. Peng, and J.D. Hong, cw laser anneal of polycrystalline silicon: Crystalline structure, electrical properties, Appl. Phys. Lett. 33 (1978), pp. 775.

[20] R.T. Young, C.W. White, G.J. Clark, J. Narayan, W.H. Christie, M. Murakami, P.W. King, and S.D. Kramer, Laser annealing of boron-implanted silicon, Appl. Phys. Lett. 32 (1978), pp. 139.

[21] M. Miyasaka and J. Stoemenos, Excimer laser annealing of amorphous and solid-phase crystallized silicon films, J. Appl. Phys. 86 (1999), pp. 5556.

[22] D. Murley, N. Young, M. Trainor, and D. McCulloch, An investigation of laser annealed and metal-induced crystallized polycrystalline silicon thin-film transistors, Electron Devices, IEEE Trans. 48 (2001), pp. 1145–1151. doi:10.1109/16.925240.
M.O. Thompson, G.J. Galvin, J.W. Mayer, P.S. Peercy, J.M. Poate, D.C. Jacobson, A.G. Cullis, and N.G. Chew, Melting temperature and explosive crystallization of amorphous silicon during pulsed laser irradiation, Phys. Rev. Lett. 52 (1984), pp. 2360–2363. doi:10.1103/PhysRevLett.52.2360

J. Bonse, S. Baudach, J. Krüger, W. Kautek, and M. Lenzner, Femtosecond laser ablation of silicon—modification thresholds and morphology, Appl. Phys. A. 74 (2002), pp. 19–25. doi:10.1007/s003390100893

A.E. Bell, Review and analysis of laser annealing, RCA Review 40 (1979), pp. 295.

S. Kawamura, J. Sakurai, M. Nakano, and M. Takagi, Recrystallization of Si on amorphous substrates by doughnut-shaped cw Ar laser beam, Appl. Phys. Lett. 40 (1982), pp. 394.

J. Jia, M. Li, and C.V. Thompson, Amorphization of silicon by femtosecond laser pulses, Appl. Phys. Lett. 84 (2004), pp. 3205.

J. Bonse, All-optical characterization of single femtosecond laser-pulse-induced amorphization in silicon, Appl. Phys. A. 84 (2006), pp. 63–66. doi:10.1007/s00339-006-3583-3

F. Costache, S. Kouteva-Arguirova, and J. Reif, Sub-damage-threshold femtosecond laser ablation from crystalline Si: Surface nanostructures and phase transformation, Appl. Phys. A. 79 (2004), pp. 1429. doi:10.1007/s00339-004-2803-y

M. Schade, O. Varlamova, J. Reif, H. Blumtritt, W. Erfurth, and H.S. Leipner, High-resolution investigations of ripple structures formed by femtosecond laser irradiation of silicon, Anal. Bioanal. Chem. 396 (2010), pp. 1905–1911. doi:10.1007/s00216-009-3342-3

M. Straub, M. Schüle, M. Afshar, D. Feili, H. Seidel, and K. König, Sub-15 fs femtosecond laser-induced nanostructures emerging on Si(100) surfaces immersed in water: Analysis of structural phases, Appl. Phys. A. 115 (2014), pp. 221–228. doi:10.1007/s00339-013-7980-0

H. Richter, Z.P. Wang, and L. Ley, The one phonon Raman spectrum in microcrystalline silicon, Solid State Commun. 39 (1981), pp. 625–629. doi:10.1016/0038-1098(81)90337-9

M. Shen, Raman phonons of silicon wires, Phys. Lett. A 180 (1993), pp. 295–298. doi:10.1016/0375-9601(93)90714-B

A.T. Voutsas, M.K. Hatalis, J. Boyce, and A. Chiang, Raman spectroscopy of amorphous and microcrystalline silicon films deposited by low-pressure chemical vapor deposition, J. Appl. Phys. 78 (1995), pp. 6999.

B. Li, D. Yu, and S. Zhang, Raman spectral study of silicon nanowires, Phys. Rev. B 59 (1999), pp. 1645–1648. doi:10.1103/PhysRevB.59.1645

Z. Iqbal and S. Veprek, Raman scattering from hydrogenated microcrystalline and amorphous silicon, J. Solid State Phys. 15 (1982), pp. 377–392. doi:10.1088/0022-3719/15/2/019

X.L. Wu, G.G. Siu, S. Tong, X.N. Liu, F. Yan, S.S. Jiang, X.K. Zhang, and D. Feng, Raman scattering of alternating nanocrystalline silicon/amorphous silicon multilayers, Appl. Phys. Lett. 69 (1996), pp. 523.

R. Saleh and N.H. Nickel, Raman spectroscopy of B-doped microcrystalline silicon films, Thin Solid Films. 427 (2003), pp. 266–269. doi:10.1016/S0040-6090(02)01203-8

X.C. Wang, H.Y. Zheng, C.W. Tan, F. Wang, H.Y. Yu, and K.L. Pey, Femtosecond laser induced surface nanostructuring and simultaneous crystallization of amorphous thin silicon film, Opt. Express 18 (2010), pp. 18.

G. Ghosh, Handbook of Optical Constants of Solids, Academic Press, New York, 1998.