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Effects of spacer thickness on quantum efficiency of the solar cells with embedded Ge islands in the intrinsic layer

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We report on the effects of spacer thickness on the external quantum efficiency (EQE) of the solar cells with Ge islands embedded into the intrinsic region of the Si-based p-i-n diode. The EQE response of the solar cells in the near-infrared region is dependent on the spacer thickness that separates the layers of self-assembled Ge islands. It was found that the EQE response has an optimum value when the spacer thickness can sustain a good vertical ordering of islands. On the other hand, random nucleation of islands due to a thicker spacer layer exhibits an inferior EQE response. Furthermore, a drastic decrease of the EQE response of the solar cells for a thinner spacer layer was observed. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1697632]

Much effort has been devoted by many researchers to enhance the performance of solar cells by efficiently absorbing the subband gap light. Recent theoretical predictions include the utilization of intermediate band solar cells,[1] upconversion for the absorption of subband gap light,[2] and control of the strain, shape, and local Ge fraction in multicrystalline SiGe for the absorption of the near-infrared light.[3] Furthermore, experimental innovations were also performed to improve the performance of the solar cells by absorbing the low-energy photons, i.e., to utilize SiGe multicrystalline with microscopic compositional distribution[4,5] to enhance the absorption performance, and to exploit the advantage of quantum well solar cells to independently optimize the absorption edge and spectral characteristics.[6]

Another way to absorb the low-energy photon is to incorporate Ge dots in the intrinsic region of Si-based solar cells. An experimental attempt was already carried out; however, the spectral response in the near-infrared region was not observed, instead it was suggested that further experiments should be done.[7] Recently, we reported on the enhanced performance of the external quantum efficiency (EQE) in the near-infrared region utilizing Ge dots stacked in multilayer structure.[8] The EQE was found to increase with increasing number of Ge islands stacked layers.[9] Our current results were already significant however, exploring an optimum EQE response in the near-infrared region is highly stimulating.

In this letter, we present the effects of the spacer thickness on the EQE in the lower photon energies of solar cells with Ge dots embedded in the intrinsic region of the Si-based p-i-n diode. We point out that optimization of spacer thickness is important to achieve an optimum EQE response utilizing low-energy photons. Good vertical ordering of islands was observed and exhibits an excellent EQE response when compared with the thicker spacer layer that triggers random island nucleation. Thinner spacer thickness showed a drastic decrease of the EQE of the solar cells. The effects of spacer thickness on the strain fields and stacking faults in the multilayer structure are discussed based on the transmission electron microscopy (TEM) images and PL spectra.

The investigated solar cells were grown on p-type Si(100) with a resistivity of 1–10 Ω cm substrate using a gas-source molecular-beam epitaxy (AirWater VCE S2020) system. Pure Si_2H_6 and GeH_4 were used as source gases. The growth process and other experimental details can be found elsewhere.[8] The nominal thickness of the spacer layer was varied systematically ($d_s = 10$, 39, and 100 nm). This refers to the thickness between adjacent wetting layers, not the thickness between islands. Both the islands and the spacers are in the very lightly doped region. The schematic illustration of the completed solar cell device is shown in Fig. 1.

The structural properties of these samples were characterized with cross-sectional TEM. The Pl and EQE measurements are previously described elsewhere.[9]

The EQE of the solar cells in the near-infrared region with Ge dots separated by different spacer thicknesses are shown in Fig. 2. It is very obvious that solar cells with Ge dots embedded into the intrinsic region of the Si-based p-i-n diode significantly increased the EQE response up to 1.45 μm. On the other hand, the solar cells without Ge islands in the intrinsic region showed a spectral response up to 1.20 μm only, which corresponds to the band edge of silicon. It is worth noting that the EQE performance drastically decreases to 1.30 μm for the solar cells with 10 nm spacer width. Furthermore, the solar cells with a 100 nm spacer thickness display an inferior EQE response compared with that of the 39 nm spacer thickness. The enhanced absorption performance of the solar cells in the lower photon energies is attributed to the presence of Ge islands in the intrinsic layer. The EQE increase in the near-infrared region is a manifestation that the spacer thickness that separates the Ge islands

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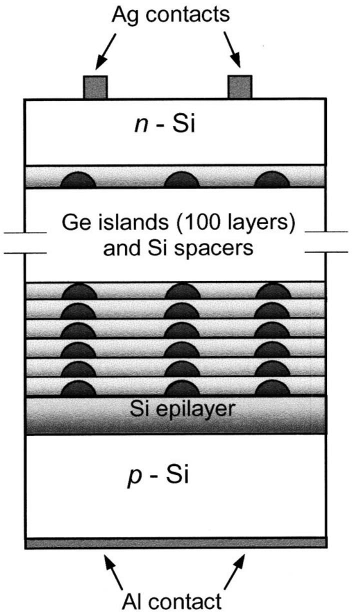

FIG. 1. Schematic illustration of the completed solar cells with 100 layer of stacked Ge islands embedded into the intrinsic region of the *p-i-n* diode.

indeed plays a vital role in the enhanced performance of the solar cells. Figure 2 shows that the overall spectral response of the solar cells with Ge dots in the intrinsic region is not inferior to the Si-based solar cells and the EQE in the lower wavelengths. Consequently, the ratio of the solar cells with Ge dots over the Si-only reference cell is increased by ≈1.16.[13]

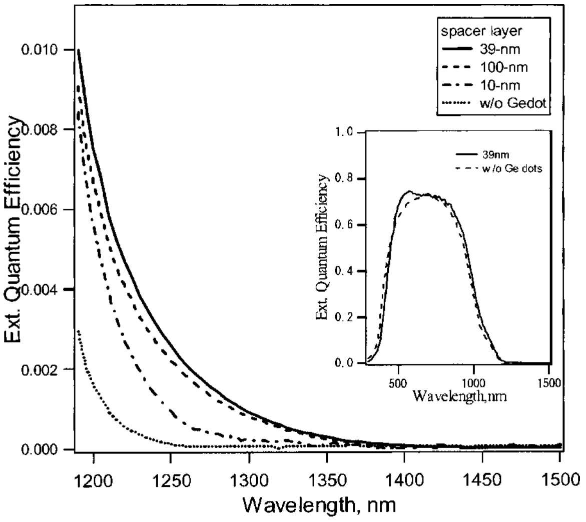

FIG. 2. Spacer thickness dependence of EQE response of the solar cells in the near-infrared region with 100 layer of stacked Ge islands. EQE of the solar cells without Ge islands in the intrinsic region is also shown. The overall EQE response of the solar cells with and without Ge dots is shown in the inset.

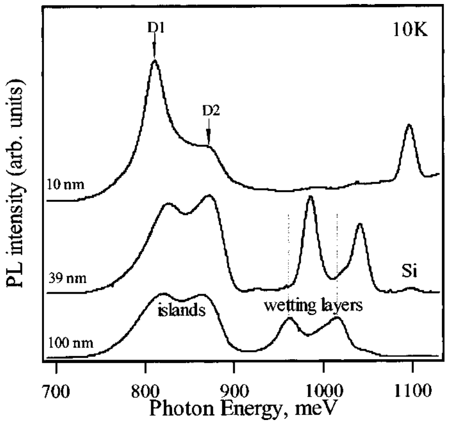

FIG. 3. 10 K PL spectra of 100 layer of stacked Ge islands with different spacer thicknesses.

The PL spectra of the samples with 100 layer stacked Ge islands of different spacer thicknesses are shown in Fig. 3. The PL line at around 1100 meV can be assigned to Si-related peak. The spacer thicknesses of $d_s = 39$ and 100 nm with PL broad lines at around 800 and 900 meV correspond to Ge islands. The two broad peaks correspond to the no-phonon (NP) and transverse optical (TO) replica coming from the Ge islands luminescence due to their energy difference (i.e., $\Delta E \approx 55$ meV). An alternative explanation of the presence of these peaks might be attributed to the bimodal distribution of Ge islands as suggested in the previous reports.[14,15] The reduction in spacer thickness to $d_s = 10$ nm, two unique peaks, relatively sharper than those from thicker spacer layers, are obviously noticeable around 812 and 875 meV. These line emissions are similar to the dislocation-related D line in Si which is assigned as $D1$ and $D2$ lines, respectively.[16] This D-line luminescence originates from the kinks and jogs associated with dislocations introduced by plastically deformed silicon.

For samples having a thicker spacer layer, $d_s = 100$ nm, the PL lines around 960 and 1016 meV obviously correspond to wetting layers due to their energy difference. These can be assigned as excitonic NP and TO phonon assisted emissions, respectively. On the other hand, the blueshift of the PL lines was observed when $d_s = 39$ nm. This is due to the occurrence of material intermixing Ge island layers and Si spacers during growth at 700 °C.[17,18] Another explanation to resolve this blueshift phenomenon for a thinner spacer thickness might be the presence of a thinner wetting layer triggered by stronger strain field modulations influenced by the buried islands.[19,20] For a further reduction in spacer thickness to $d_s = 10$ nm, the PL lines assigned to wetting layers disappeared. Possible reasons for this might be the extreme thinning of the wetting layer around the surface that could no longer produce signal or that most of the carriers are trapped in the dislocations and recombined there.

To explore the nature of the PL lines and their associated dislocations, TEM investigations were employed. Figures 4(a)–4(c) show typical cross-sectional bright-field TEM images of Ge islands stacked in a multilayer structure with different spacer thicknesses. As depicted in Fig. 4(a), the apparent vertical correlation between Ge islands is clearly observed. The average separation distance from the top of the Ge dots to the bottom of the next succeeding island is approximately ≈7.8 nm. The image in Fig. 4(a) clearly shows that every island in the upper layers grow directly on the top of the buried islands. This phenomenon is a consequence of the elastic strain fields created by the buried islands in the lower layers.[21]

For a thicker spacer, $d_s = 100$ nm, the strain fields of the buried islands are too weak to provide any effects on the formation of the upper layer, as shown in Fig. 4(b). The Ge

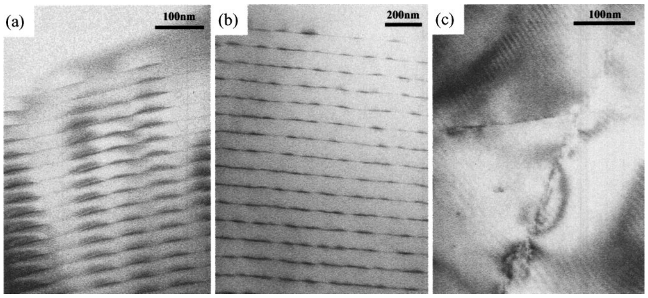

FIG. 4. TEM images of stacked Ge islands with different spacer thickness (a) $d_s=39$ nm, strong vertical ordering showing the topmost portion of the 100 layer Ge islands. (b) $d_s=100$ nm, showing the uppermost portion of the structure. (c) $d_s=10$ nm, showing the dislocations.

island distributions at the top layer of the structure are comparable with that of the initial layer. Thus, ordering of islands is less probable.

Figure 4(c) shows the lowermost portion of the multilayered structure with $d_s=10$ nm. It is very obvious that dislocations occurred in the multistacked structure which penetrate through the stacked layers and even extended deeply toward the Si substrate. This observation is consistent with the presence of D line in the PL spectra shown in Fig. 3. These dislocations are the consequence of a plastically deformed crystal since the height of the buried islands is greater than the thickness of the spacer layer. For a narrow spacer width, a highly strained Si layer is situated in the multistacked structure. The total strain energy of the sample having a thin spacer layer is greater than that of the thicker spacer layer due to the accumulation of strain.[22,23] If the total strain energy would be greater than the energy needed for dislocation generation, then the possible dislocation emerged.

It is important to emphasize that the presence of dislocations greatly affects the electrical and photovoltaic properties of a device. It is believed that dislocations accompany some deep levels which act as active recombination centers that will drastically affect the minority carrier lifetime and diffusion lengths of the solar cells. The recombination losses in the dislocations sites will further deteriorate the EQE performance of the photovoltaic devices.

Furthermore, it is speculated that this enhanced EQE performance may be due to the thermal escape in which the carrier probably escapes from the Ge dots and/or wetting layers and move sequentially until they will be collected in the conduction band for current generation before recombining[10,11] or may be due to the vertical correlation of the stacked Ge islands that stimulate electronic coupling between aligned dots, and channeling of electrons and holes might occur.[12]

Finally, the importance of spacer thickness to achieve an optimum EQE response of the solar cells should be emphasized. The proper selection of spacer thickness that separates the layers of Ge islands could properly enhance the performance of the photovoltaic device. The results strongly suggests that the optimization of structural parameters, such as spacer layer thickness, is highly needed to achieve an optimum EQE response of solar cells.

In conclusion, we reported the effects of spacer thickness on the EQE of solar cells in the near-infrared region with Ge islands stacked in a 100 layer structure. The optimum EQE response of solar cells is dependent on the spacer thickness that separates layers of Ge islands. It was speculated that either sequential transport through thermal escape or electronic coupling through vertical ordering of islands might be responsible for the substantial improvement of the EQE performance of the solar cells. A drastic decrease in the EQE performance was observed for a thinner spacer thickness. This was due to the presence of kinks and jogs associated with dislocations in the structure.

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[1] L. Cuadra, A. Martí, and A. Luque, Physica E (Amsterdam) **14**, 162 (2002).
[2] T. Trupke, M. A. Green, and P. Würfel, J. Appl. Phys. **92**, 4117 (2002).
[3] N. Usami, T. Ichitsubo, T. Ujihara, T. Takahashi, K. Fujiwara, G. Sazaki, and K. Nakajima, J. Appl. Phys. **94**, 916 (2003).
[4] K. Nakajima, N. Usami, K. Fujiwara, Y. Murakami, T. Ujihara, G. Sazaki, and T. Shishido, Sol. Energy Mater. Sol. Cells **73**, 305 (2002).
[5] K. Nakajima, N. Usami, K. Fujiwara, Y. Murakami, T. Ujihara, G. Sazaki, and T. Shishido, Sol. Energy Mater. Sol. Cells **72**, 93 (2002).
[6] K. W. J. Barnham and G. Duggan, J. Appl. Phys. **67**, 3490 (1990).
[7] J. Konle, H. Presting, H. Kibbel, and F. Banhart, Mater. Sci. Eng., B **89**, 160 (2002).
[8] A. Alguno, N. Usami, T. Ujihara, K. Fujiwara, G. Sazaki, K. Nakajima, and Y. Shiraki, Appl. Phys. Lett. **83**, 1258 (2003).
[9] N. Usami, A. Alguno, T. Ujihara, K. Fujiwara, G. Sazaki, K. Nakajima, K. Sawano, and Y. Shiraki, Sci. Tech. Adv. Mater. **4**, 367 (2003).
[10] S. Sanguinetti, M. Henini, M. Grassi Alessi, M. Capizzi, P. Frigeri, and S. Franchi, Phys. Rev. B **60**, 8276 (1999).
[11] A. Zachariou, J. Barnes, K. W. J. Barnham, J. Nelson, E. S. M. Tsui, J. Epler, and M. Pate, J. Appl. Phys. **83**, 877 (1998).
[12] G. S. Solomon, J. A. Trezza, A. F. Marshall, and J. S. Harris, Jr., Phys. Rev. Lett. **76**, 952 (1996).
[13] A. Alguno, N. Usami, W. Pan, K. Sawano, K. Fujiwara, T. Ujihara, G. Sazaki, Y. Shiraki, and K. Nakajima (unpublished).
[14] G. Medeiros-Ribeiro, A. M. Bratkovski, T. I. Kamins, D. A. A. Ohlberg, and R. S. Williams, Science **279**, 353 (1998).
[15] O. G. Schmidt, C. Lange, and K. Eberl, Appl. Phys. Lett. **75**, 1905 (1999).
[16] N. A. Drosdov, A. A. Patrin, and V. D. Takachev, Sov. Phys. J. Exp. Theor. Lett. **23**, 597 (1976).
[17] S. A. Chaparro, J. Drucker, Y. Zhang, D. Chandrasekhar, M. R. McCartney, and D. J. Smith, Phys. Rev. Lett. **83**, 1199 (1999).
[18] O. G. Schmidt and K. Eberl, Phys. Rev. B **61**, 13721 (2000).
[19] O. G. Schmidt, O. Kienzle, Y. Hao, K. Eberl, and F. Ernst, Appl. Phys. Lett. **74**, 1272 (1999).
[20] N. Usami and Y. Shiraki, Thin Solid Films **369**, 108 (2000).
[21] J. Tersoff, C. Teichert, and M. G. Lagally, Phys. Rev. Lett. **76**, 1675 (1996).
[22] R. People and J. C. Bean, Appl. Phys. Lett. **47**, 322 (1985).
[23] K. Nakajima, J. Cryst. Growth **126**, 511 (1993).