Electron. Mater. Lett., Vol. 10, No. 4 (2014), pp. 857-861
DOI: 10.1007/s13391-013-3305-x

Effect of Cell Gap on Electro-Optical Properties of Polymer Dispersed Liquid Crystal Lens for Smart Electronic Glasses

Jaeyong Kim and Jeong In Han*

Department of Chemical and Biochemical Engineering, Dongguk University-Seoul, Seoul 100715, Korea

(received date: 24 October 2013 / accepted date: 5 December 2013 / published date: 10 July 2014)

Polymer dispersed liquid crystal (PDLC) lenses with a cell gap of 11 μm and 30 μm were made from a uniformly dispersed mixture of 40% prepolymer (NOA 65, Norland optical adhesive 65) and 60% E7 liquid crystal. PDLC's mixture between two ITO coated glasses was polymerized by UV (ultraviolet) curing in the polymerization induced phase separation (PIPS) process. Decline of cell gap is a physical approach to improve the electro-optical properties, while cooling or doping of SiO_2 nanoparticles is the microstructural approach to enhance the properties, because the electric field applied to the liquid crystal molecules in LC droplets is inversely proportional to the cell gap. A smaller cell gap significantly and effectively increases the electric field applied to PDLCD devices. The driving voltages and slope for the sample with a cell gap of 11 μm and 30 μm were drastically improved. The driving voltage and the slope of the linear region of PDLC lens with narrow cell gap of 11 μm were drastically enhanced compared to those of the samples with 30 μm cell gap and the cooled and doped samples. These improvements were due to the increase of the applied electric field. However, the response time and contrast ratio were deteriorated. It seems that this deterioration was caused by the sticking or fixing of liquid crystal molecules in LC (liquid crystal) droplets by the intensive electric field applied to the PDLC device.

Keywords: polymer dispersed liquid crystal, cell gap, PDLC, electronics glasses, auto-shading, auto-focusing

1. INTRODUCTION

Many papers on smart electronic glasses (e-glasses) with various functions have been reported.[1-7] PDLC lens has been developed for smart e-glasses for auto-shading and auto-focusing functions. Auto-shading is the ability of the e-glasses to automatically expand or reduce the amount of external light, through automatic enlarging and closing of an aperture when the external light is weak and strong, respectively. Auto-focusing is the function of the automatic control of the focal length with the distance from the subject.

However, the electro-optical properties need to be much more improved. Especially the driving voltage must be reduced to conserve battery power of the portable devices, such as smart electronic glasses. Also, the slope of the linear region, the response times and contrast ratio of PDLC lens have to be enhanced to attain smart functions, such as the auto-shading, and auto-focusing.

Generally, it is known that UV irradiation raised the temperature at the surface of the PDLC sample due to the very high power of UV. It looks that the high temperature elevated by UV irradiation will affect the PIPS process and result in the change of the electro-optical properties of PDLC lens device. Cooling during UV curing seems to be necessary to improve the electro-optical properties.

Generally, the electric field applied to the liquid crystal molecules in LC droplets is inversely proportional to the cell gap. Thus, the electro-optical properties of PDLC lens with a smaller cell gap of 11 μm should be studied to investigate the effect of cell gap on the electro-optical properties of PDLC lens samples. In previous work,[1-5] samples with a cell gap of 30 μm were made conventionally. Therefore, in this paper, the samples with a cell gap less than 30 μm were fabricated and analyzed. Also, their electro-optical properties were compared to each other. The microstructure of PDLC devices and the arrangement of liquid crystal in LC droplets were controlled to improve the electro-optical properties through cooling or doping of SiO_2 nanoparticle technologies. A smaller cell gap significantly and effectively increases the electric field applied to PDLCD devices. Reduction of cell gap is the physical approach to improve the electro-optical properties, while cooling or doping is the microstructural approach to enhance them. Also, in this work, besides comparing the electro-optical properties of conventional and smaller cell gap, the electro-optical properties of the samples made by microstructure-controlling method were compared to that of the sample with a smaller cell gap.

There are two types for the presenting the electro-optical properties of the optical device. One is the electro-optical properties such as the intensity of light, the transmittance, the reflectance,[11] the efficiency[12] and so on with the wavelength.

---

*Corresponding author: hanji@dongguk.edu

The other is the plot of the transmittance or the intensity of the light. In this work, owing to the characteristics of PDLC lens device, the optical transmittance-voltage curves were measured by varying the applied voltage at fixed wavelength of 620 nm.

2. EXPERIMENTAL PROCEDURES

The fabrication process of polymer dispersed liquid crystal lens device was minutely described in the previous paper.[1,2] For PDLC lens fabrication, NOA 65 (Norland Products) and nematic LC E7 were uniformly mixed as the pre-polymer and nematic LC mixture, respectively. NOA 65 is an ultraviolet (UV) curable optical adhesive, since it is a mixture of trimethylopropane diallyl ether, trimethylolpropanetris thiol, isophorone diisocyanate ester and a benzophenone photo-initiator,[8,9] Nematic liquid crystal E7 is made up of 4-pentyl-4'-cyanobiphenyl (5CB), 4-heptyl-4'-cyanobiphenyl (7CB), 4-octyloxy-4'-cyanobiphenyl (8OCB), and 4-pentyl-4'-cyanoterphenyl (5CT).[9,10] E7 was prepared by homogeneous mixing of 51 wt. % of 5CB, 25 wt. % of 7CB, 16 wt. % of 8OCB, and 8 wt. % of 5CT at 75°C, which is a higher temperature than a nematic-to-isotropic transition temperature of 61.0. The mixing ratio of NOA 65 and E7 was fixed as 40 : 60. PDLC devices were fabricated by sandwiching a NOA 65 and E7 mixture between two 30 × 40 mm^2 ITO coated glass plates with the cell gap maintained at 30 μm using PMMA (Poly(methyl methacrylate)) ball spacers with a uniform diameter of 30 μm. Some with the cell gap of 11 μm were made using PMMA polymer ball spacers or a PET film spacer 11 μm thick to investigate the effect of cell gap on the electro-optical properties of PDLC lens samples. For the PDLC lens, the uniform mixture of 40% NOA 65 prepolymer - 60% E7 LC was polymerized using an UV lamp (USHIO) at 780 μW/cm^2 at 365 nm and separated into two phases of solid polymer and E7 liquid crystal LC droplets. The surface of each UV cured PDLC device was observed by optical microscope and scanning electron microscopy (SEM). The electro-optical properties of the PDLC device were measured, as described in the previous work.[1,2] A He-Ne laser with a wavelength of 620 nm and a photodetector were used for the light source and detector to measure the electro-optical properties. Also, the electro-optical properties were measured using a digital oscilloscope, function generator, power amplifier, and digital multimeter. Transmittance changes - applied voltage curves for various PDLC devices, the rising and decay (or falling) response times, and contrast ratios were measured. Slopes of the linear region in the optical transmittance-voltage curves with the applied voltage of the PDLC devices were obtained for versions of smart e-glasses, including active shutter glasses for 3D HDTV, and smart glasses with auto-shading and/or auto-focusing functions. Rising and decay response times were measured at an applied voltage of 40 V, which is sufficiently higher voltage for the transmittance saturation. Rising and falling response times were measured at an applied voltage of 40 V using a digital oscilloscope and function generator. Contrast ratios were calculated by measuring the light transmittances of the on-state and the off-state of PDLC lenses.

In this work, the samples, basically the samples with a cell gap of 30 μm, were prepared from the mixture of 40% NOA 65% - 60% E7 LC cured by a UV intensity of 780 μW/cm^2. This fabrication condition of LC concentration and UV intensity for the PDLC device could be termed reference conditions in this paper. Some with a cell gap of 11 μm were made using PMMA polymer ball spacer or PET film spacer 11 μm thick to investigate the effect of cell gap on the electro-optical properties of PDLC lens samples. Among the samples prepared in the reference condition, for the comparison of the electro-optical properties, some were cooled using a water cooling plate during the UV curing process and SiO_2 nanoparticles were added to the uniform mixture of NOA 65 and LC E7, so called doped with SiO_2 nanoparticles.

3. RESULTS AND DISCUSSION

Figure 1 displays the optical transmittance - applied voltage curves of variously treated PDLC devices with cell gaps of 11 μm and 30 μm. Also, the optical transmittance - applied voltage curves of the samples cooled using a water cooling plate during the UV curing process and the devices doped with SiO_2 nanoparticles are included in Fig. 1. Basically all the samples with a cell gap of 30 μm were prepared from the mixture of 40% NOA 65% - 60% E7 LC cured by a UV intensity of 780 μW/cm^2. In Fig. 1, the transmittance – voltage curve of cell gap 11 μm corresponds to that of the samples with a cell gap of 11 μm fabricated in

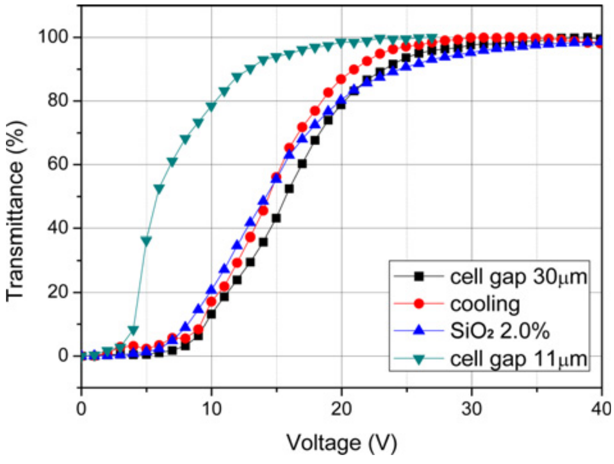


Fig. 1. Optical transmittance-voltage curves of various PDLC lens devices of cell gap 30 μm, cell gap 11 μm, cooling and SiO_2 2.0%.

the reference condition. The only difference between the cell gap 30 μm and cell gap 11 μm of Fig. 1 is the distance between the two ITO coated glasses, i.e. the cell gap. The notation of cooling in Fig. 1 means that the PDLC lens device with a cell gap of 30 μm was prepared from the mixture of 40% NOA 65% - 60% E7 LC cured by a UV intensity of 780 μW/cm^2 and cooled on a water cooling plate during the UV curing process. The difference between cell gap 30 μm and cooling in Fig. 1 is only the addition of the cooling process during UV curing. Also, the transmittance-voltage curve of the sample fabricated from the reference condition and added SiO_2 nanoparticles of a concentration of 2.0% in the mixture of 40% NOA 65% - 60% E7 LC is presented in Fig. 1 and expressed as SiO_2 2.0%. The optical transmittance-voltage curves of cell gap 30 μm,[1,2] cooing and SiO_2 2.0% are the same curves as that of previous work.

From the transmittance-voltage curves in Fig. 1, the driving voltages for the sample of cell gap 30 μm, cell gap 11 μm, cooling and SiO_2 2.0% were 23.3 V, 12.0 V, 19.7 V and 22.8 V, respectively and are given in Fig. 2. The driving voltage of cell gap 11 μm is just half that of the sample of cell gap 30 μm prepared from the reference condition. This level of the driving voltage is very attractive for the application of liquid crystal lens for smart electronic glasses.

From Fig. 1 and Fig. 2, the driving voltage could be improved by various fabrication methods, such as the cooling during UV curing process and the doping of SiO_2 nanoparticle, and the reduction of the cell gap. Among them, the effect of reduced cell gap on the driving voltage exhibited the best data of 12.0 V. The effects of cooling and doping on the driving voltages of PDLC lens are based on the arrangement of liquid crystal molecules in LC droplets. That is, the arrangement of liquid crystal molecules in LC droplets could be controlled by cooling during the UV curing process or doping of SiO_2 nanoparticles. The driving voltage was improved from 23.3 V to 19.7 V though controlling homogeneous nucleation of the LC droplet and the arrangement of liquid crystal molecule in the LC droplet by cooling during the UV curing process. Also, the heterogeneous nucleation at the surface of SiO_2 nanoparticles and the arrangement of liquid crystal molecules were induced to reduce the driving voltage by the addition of SiO_2 nanoparticles. The effect of a small cell gap is to increase the applied voltage by the change of critical physical distance of the cell gap, not for the arrangement of liquid crystal molecules in LC droplets formed by homogeneous or heterogeneous nucleation. The electric field applied to the liquid crystal molecules in LC droplets is inversely proportional to the cell gap. It can be concluded that the substantial increase of the electric field applied to the lens device is the most effective, rather than from controlling the microstructure of PDLC. The enhancement of the driving voltage by a small cell gap is more effective than by delicate control of the microstructure of PDLC lens, because the improvement of the driving voltage is in order: cell gap 11 μm, cooling, SiO_2 doping and cell gap 30 μm.

Figure 3 shows the variations of the slope in the linear regions of the optical transmittance - applied voltage curves for the samples with a cell gap of 30 μm, cell gap of 11 μm, cooling and SiO_2 doping. The improvement of the slope is in the order of cell gap 11 μm, cooling, cell gap 30 μm and SiO_2 doping. Actually, the increase of the slope was not so much caused by the reduction of cell gap from 30 μm to 11 μm. The slope is more dependent on the microstructure and the arrangement of liquid crystal molecules in LC droplets than that of the driving voltage. Thus, it can be conceived that the control of the microstructure and the arrangement of liquid crystal molecules in LC droplets by cooling or doping are more important than the increase of the electric field to PDLC device by the cell gap control to improve the slope properties of smart electronic glasses. The cooling and SiO_2 doping were discussed to form the liquid crystal molecule arrangement well, the so called well aligned

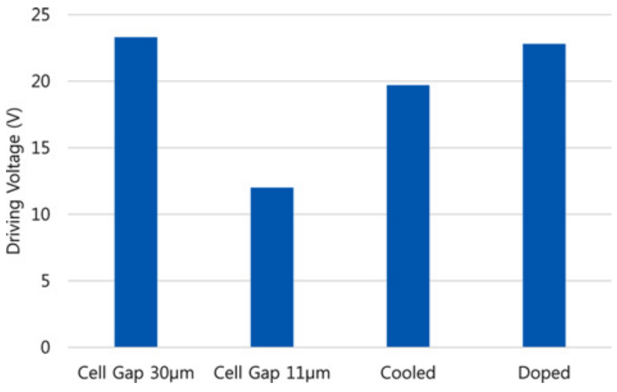


Fig. 2. Driving voltages of various PDLC lens devices of cell gap 30 μm, cell gap 11 μm, cooling and SiO_2 2.0%.

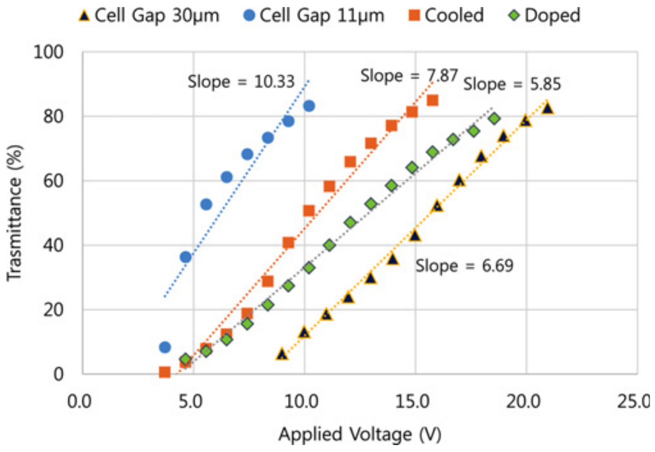
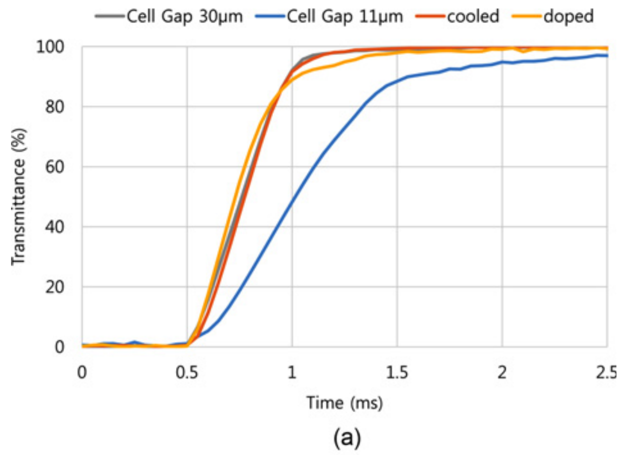
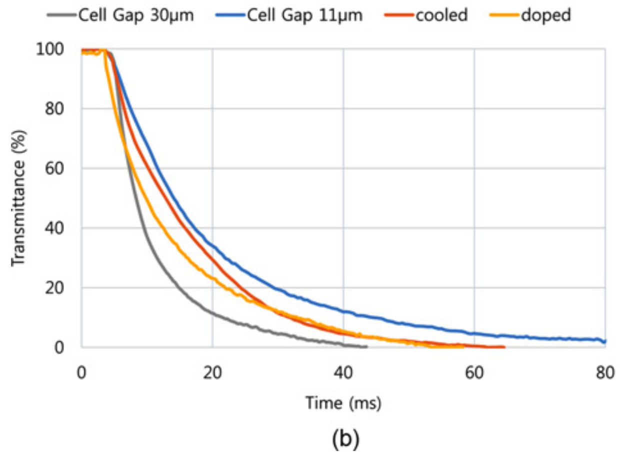


Fig. 3. Slope of the linear regions of the transmittance-voltage curves of various PDLC lens devices of cell gap 30 μm, cell gap 11 μm, cooling and SiO_2 2.0%.



(a)



(b)

Fig. 4. (a) rising response times and (b) falling response times of various PDLC lens devices of cell gap 30 μm, cell gap 11 μm, cooling and SiO_2 2.0%. Both of rising and falling response time has the delay time of 0.5 s for the convenience of view.

liquid crystal molecules in LC droplets of the previous paper.

Figure 4 shows the variations of the rising and falling response times for the samples with the transmission-voltage curves of Fig. 1. The improvement of both rising response time and decay response time were not achieved by the control of the microstructure and the arrangement of liquid crystal molecules in LC droplets through the cooling or doping process. These response times were rather moderately increased. Even though the rising response times were around 1.0 ms, they were slightly increased by the modified samples by cooling or doping. For the falling response time, they were raised from 18.64 ms of cell gap 30 μm to 28.0 ms by cooling and 29.6 ms by SiO_2 nanoparticle doping. However, both rising response time and falling response time were much longer, by reducing the cell gap from 30 μm to 11 μm. Although the rising response times were small, around 1.0 ms, the rising response time of cell gap 11 μm was longer by about 2.5 times than that of cell gap 30 μm. Specifically, the decay or falling response times were significantly raised from 18.64 ms for cell gap 30 μm to 45.3 ms for cell gap 11 μm. Like the case of the rising response time, the falling response time of cell gap 11 μm was longer by about 2.5 times than that of cell gap 30 μm. These longer response times were due to the sticking or fixing of liquid crystal molecules in LC droplets by the intensive electric field applied to the PDLC device. The reduction of cell gap from 30 μm to 11 μm make the applied electric field stronger by more than 2.7 times, because the electric field applied to the liquid crystal molecules in LC droplets is inversely proportional to the cell gap. This strong electric field tends to align the liquid crystal molecules momentarily. Therefore, both rising and falling response times tend to be longer. In this work, according to the increase of the applied electric field of about 2.7 times by reducing the cell gap from 30 μm to 11 μm, the rising and decay response times of cell gap 11 μm were longer by about 2.5 times than those of cell gap 30 μm, which shows very similar relationships.

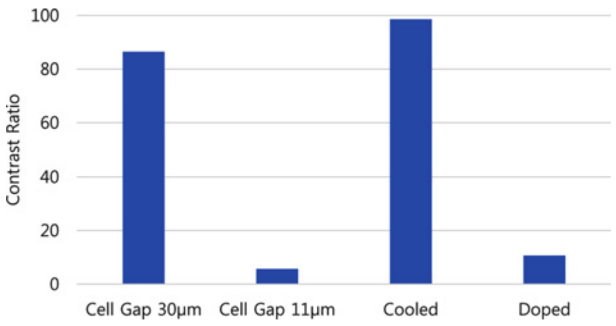


Fig. 5. Contrast ratios of various PDLC lens devices of cell gap 30 μm, cell gap 11 μm, cooling and SiO_2 2.0%.

Figure 5 shows the variations of contrast ratio for the samples with the transmission-voltage curves of Fig. 1. The contrast ratio was improved in the order of cooling, cell gap 30 μm, SiO_2 nanoparticle doping and cell gap 30 μm. In particular, the contrast ratio of cell gap 11 μm is drastically reduced to 5.7 from 86.5 of cell gap 30 μm fabricated by the reference condition and comparable to 10.7, that of the doped sample with SiO_2 nanoparticles. The contrast ratio of cell gap 11 μm corresponds to only 6.6% of the contrast ratio of cell gap 30 μm. There was a drop in contrast ratio of 93.6%. The low contrast ratio of the doped sample was discussed as being caused by the well aligned arrangement of liquid crystal molecules in LC droplets induced by a faster nucleation rate and many more nucleation sites at the surface of the SiO_2 nanoparticles. However, in this work, it seems to be due to the sticking or fixing of liquid crystal molecules in the LC droplets by the intensive electric field applied to the PDLC device. This sticking or fixing of liquid crystal molecules tends to have the same effect as the well aligned arrangement of liquid crystal molecules. Liquid crystal molecules well stuck by a strong electric field required more external force, such as the applied voltage to return to the original random arrangement at the off state. Even though it seemed that liquid molecules in LC droplets at the off state were randomly aligned, the arrangement is not seamlessly random to scatter much more light in the off state. It looks as though there is much light leakage in the off state due to there being no perfect random arrangement of liquid crystal molecules in LC droplets.

A small cell gap of the PDLC lens device is positively affected by improving the driving voltage and the slope of the linear regions of the transmittance-voltage curves for smart electronic glasses but degrades the response times and contrast ratio. The electric field applied to the liquid crystal molecules in LC droplets is inversely proportional to the cell gap. Thus, the reduced cell gap from 30 μm to 11 μm make the applied electric field stronger by more than 2.7 times. The intensified electric field contributed to the improvement of the driving voltage and the slope of the linear regions. However, the intensive electric field applied to the PDCL lens device makes liquid crystal molecules in LC droplets be strongly stuck or fixed to the on-state arrangement of for some time. This temporary sticking or fixing of liquid crystal molecules in the on-state makes the response time longer and contrast ratio worse than that of the sample from the reference conditions.

4. CONCLUSIONS

In previous work, cooling or doping of SiO_2 nanoparticle was attempted to control the microstructure to enhance the electro-optical properties, such as the driving voltage, the slope of the linear region, the response time and contrast ratio. In this work, it seems reducing the physical dimension of PDLC lens such as the cell gap was very effective. We try to improve the electro-optical properties, because the electric field applied to the liquid crystal molecules in LC droplets is inversely proportional to the cell gap.

The driving voltages for the sample with cell gaps of 30 μm and 11 μm were significantly improved by more than 2.0 times. This was moderately enhanced compared to the cooled or doped samples. The slope was also moderately enhanced when the cell gap was smaller. However, the rising and decay response times were extended by about 2.5 times and the contrast ratio diminished by more than 93.4%, as the cell gap decreased from 30 μm to 11 μm. It looks like the deterioration was due to the sticking or fixing of liquid crystal molecules in LC droplets by the intensive electric field applied to the PDLC device.

ACKNOWLEDGEMENTS

This work was supported by the Dongguk University Research Fund of 2013.

REFERENCES

1. J. Kim and J. I. Han, *Electron. Mater. Lett.* in press (2014). [DOI:10.1007/s13391-013-3223-y]
2. J. Kim and J. I. Han, *Electron. Mater. Lett.* in press (2014). [DOI:10.1007/s13391-013-3264-2]
3. J. I. Han, *Proc. Int. Conf. on Consumer Electronics 2013*, p. 338, IEEE Consumer Electronics Society, Las Vegas, USA (2013).
4. Y. J. Park, J. Kim, D. W. Kim, and J. I. Han, *Proc. Conf. on Korean Liquid Crystal Conf.,* p. 134, Korea Information Display Society, Seoul, Korea (2013).
5. Y. J. Park, J. K. Park, J. Kim, D. W. Kim, and J. I. Han, *Proc. Conf. on Korean Liquid Crystal Conf.,* p. 137, Korea Information Display Society, Seoul, Korea (2013).
6. H. Ren, Y.-H. Fan, and S.-T. Wu, *J. Phys. D : Appl. Phys.* **37**, 400 (2004).
7. V. V. Presnyakov and T. V. Galstian, *J. Appl. Phys.* **97**, 103101 (2005).
8. P. Malik, K. K. Raina, and A. K. Gathania, *Thin Solid Films* **510**, 1047 (2010).
9. S. Park, H.-K. Kim, and J. W. Hong, *Polym. Test.* **29**, 886 (2010).
10. T. Kyu, I. Ilies, and M. Mustafa, *J. Phys. IV*, **3**, 37 (1993).
11. B. S. Bae, S. Han, S. S. Shin, K. Chen, C. P. Chen, Y. Su, and G. G. Jhun, *Electron. Mater. Lett.* **9**, 735 (2013).
12. K. T. R. Reddy, P. A. Nwofe, and R. W. Miles, *Electron. Mater. Lett.* **9**, 363 (2013).