Epitaxial film bonding technology for integrating dissimilar device materials

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Abstract

We have developed "epitaxial-film-bonding (EFB)" technology for integrating light emitting diodes (LEDs) and integrated circuit (IC) drivers. This study is focused on testing the EFB technology to fabricate two-dimensional thin film LED arrays on substrates of various materials. Transferring the thin film LED device structure that were formed on the GaAs substrates to the other substrates was tested. All the thin film LED arrays tested in this study show good performance. The EFB technology will provide new "Digital Fabrication" process for integrating dissimilar materials.

Introduction

Development of technologies for integration of electronic and optical devices has been a big issue for long time. We have developed "epitaxial-film-bonding (EFB)" technology for integrating light emitting diodes (LEDs) and integrated circuit (IC) drivers for LED printer printheads [1,2]. In the EFB technology, epitaxial film (single crystal semiconductor thin film) is peeled off from the mother substrate and bonded onto another substrate. The EFB technology provides high quality integrated device systems and is very promising technology for integrating dissimilar material devices. In the device-system fabrication by EFB, each device can be fabricated in the best fabrication process before integrating the devices.

Digital fabrication technology directly forms device structure on a substrate using digital printing processes (e.g. screen printing, ink jetting, nano inprinting). From this point of view, the EFB process for transferring a device structure from the mother substrate to another substrate is also *digital fabrication process.*

Many studies on EFB technology [3] have been carried out after the pioneering investigations by Konagai [4] and by Yabnolovitch [5]. Only few cases of mass productions of semiconductor devices using EFB technology are found so far [1, 2]. But the EFB technology seems very promising to apply in integration of LEDs and dissimilar materials.

In this study, fabrication is tested of two-dimensional thin epitaxial film LED arrays on the Si, glass and plastic substrates using the EFB technology. Two-dimensional LED arrays with two different epitaxial film materials are fabricated. Two different EFB processes to transfer epitaxial films before and after forming LED device structure are investigated. In the following section, EFB process and characteristics, design and performance of two-dimensional epitaxial film LED arrays and higher density two-dimensional epitaxial film LED array are described.

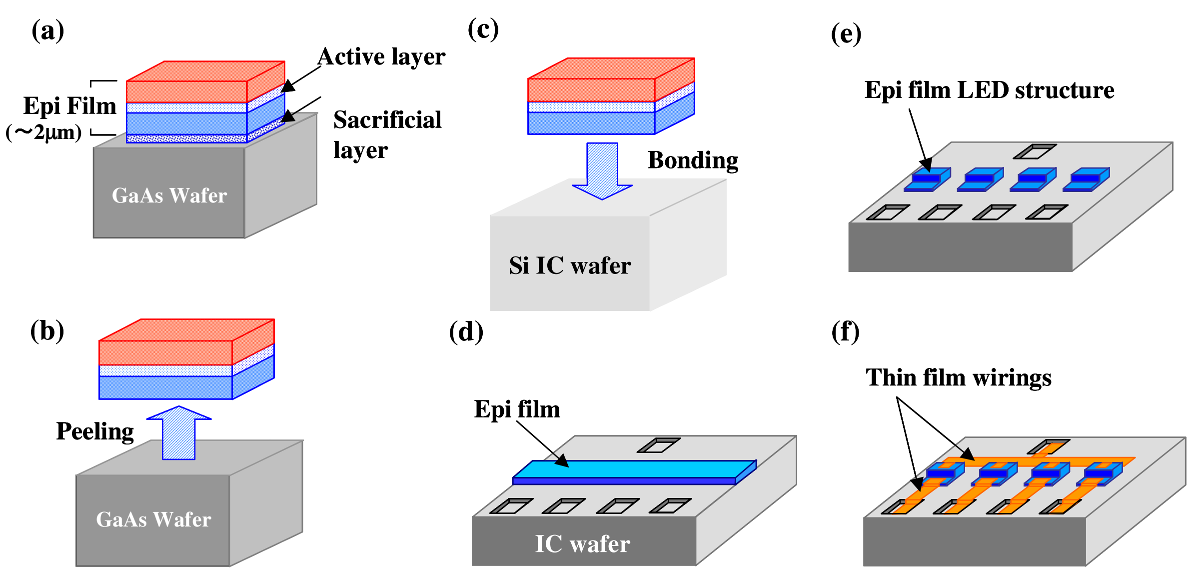

Fig. 1 EFB process outline for fabricating epitaxial film LED array integrated with IC drivers

EFB process and characteristics

EFB process outline

Figure 1 shows the schematic drawing of the EFB process. The epitaxial thin film layers of AlGaAs and GaAs are grown on the GaAs substrate by organic metal chemical vapor deposition (OMCVD); the epitaxial layer of about 2μm in thickness to form LED is called "epitaxial film" in this paper. A sacrificial layer is formed between the epitaxial film and the GaAs substrate. The epitaxial-film layer is divided into plurality of LED array areas by mesa etching. The sacrificial layer is exposed at the mesa-etched areas (a). The wafer is immersed into an etching solution to peel off the epitaxial films from the GaAs substrate. The sacrificial layers are selectively etched and the epitaxial films are peeled off from the GaAs substrate (b). Support materials are formed on the epitaxial films before immersing the wafer into the etching solution to support thin epitaxial films during the process steps of peeling, handling and bonding of the epitaxial films. The peeled epitaxial films are pressed to bond on the substrates other than GaAs (Si, glass, plastic) without using adhesives (c, d). After bonding the epitaxial films on the substrates, fabrication process of the LED arrays is carried out (e). The electrodes of the LEDs are connected to the wirings that are formed on the substrates by thin metal film (f).

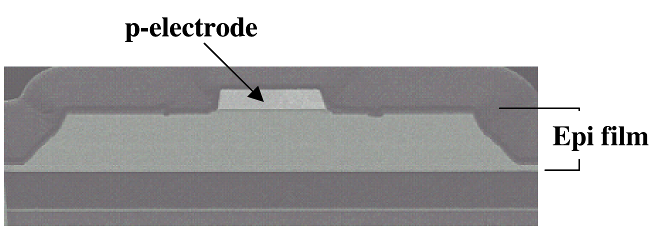

Fig. 2 SEM image of the cross section of the bonded interface of the epitaxial film LED

EFB characteristics

EFB characteristics have a large effect on LED fabrication process and the characteristics and reliability of the bonded epitaxial film LED arrays. In this subsection, bonding characteristics of the epitaxial film are described after photolithography and etching processes of the LED array and heat shock cycle test of the bonded epitaxial film LED array is described. The data described in this section are taken using the chip of the LED array that is integrated with the IC drivers for the LED printhead.

Figure 2 shows the scanning electron microscope (SEM) image of the cross section of the bonded interface of the epitaxial film and the smoothing layer on the Si IC wafer. As shown in Fig. 2, the epitaxial film is well bonded on the smoothing layer on the IC drivers. No void at the bonding interface and no crack in the bonded epitaxial film are observed. This indicates that the bonding strength of the epitaxial film on the bonding region is strong enough for fabricating the LED array by photolithography and processes of etching and forming insulating thin film and metal thin film.

Figure 3 shows the result of the heat shock cycle test of the LED arrays that are bonded on the Si IC wafer. The heat shock cycle is [85°C x 30min / -40°C x 30min] x 100cycles. The number of the LEDs in one LED array chip is 192. 26 pieces of the LED array chips are mounted on a printed circuit board. Total number of the LEDs on the printed circuit board is 4992. As shown in Fig. 3, the emitted light power of each LED does not change after heat shock cycles. This indicates that EFB characteristics do not change during the heat shock test; void at the bonding interface and crack in the bonded epitaxial film do not appear. The EFB characteristics are proven good enough to form the epitaxial film LED array.

Design of two-dimensional LED array

Figure 4 shows the schematic drawing of the design of the two-dimensional LED array. As shown in Fig. 4, the epitaxial film LEDs (300μm x 300μm) are disposed in two-dimensional LED array (24 dots x 24 dots). The pitch of the epitaxial film LEDs is 600μm. Both of the n-type side and p-type side electrodes are formed on the surface side of the LED.

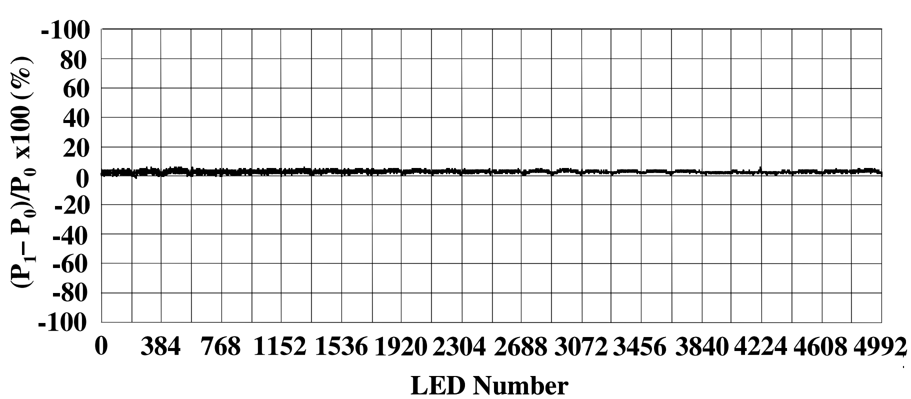

Fig. 3 Heat shock cycle test result of the LED array. P_0 and P_1 indicate emitted light intensities before and after heat shock cycle

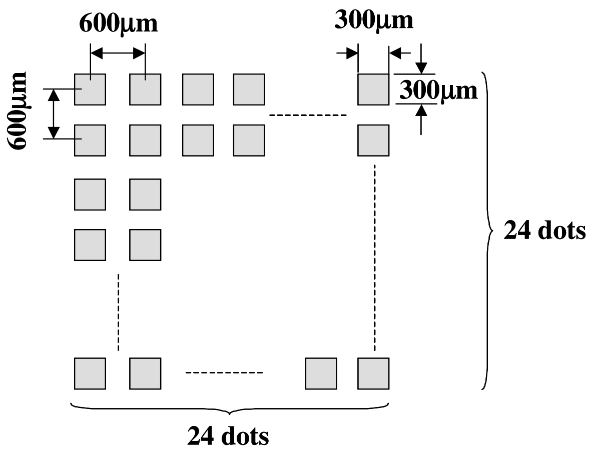

Fig. 4 Design of the two-dimensional LED array

the epitaxial films 1 and 2 are chemically peeled of from the GaAs substrates as described in the subsection of EFB process outline.

In this fabrication test of the two dimensional LED arrays, two types of EFB processes are tested. One type of the fabrication process is that the LED array is formed after bonding the epitaxial films on the substrates (process I). Another type of the fabrication process is that the LED array is bonded after fabricating the LED device structure (process II).

Figure 5 shows the process outline of the process II. As shown in Fig. 5, the LED array device structure is formed on the GaAs substrate (a). The LED arrays are peeled off from the GaAs substrate by selectively etching the sacrificial layers (b). The peeled epitaxial film LED arrays are bonded on the other substrates than GaAs (c, d).

The matrix structure of the p-type side and n-type side wirings are formed on the substrate and are connected to the electrodes of the LED array. The matrix wiring can operate each LED individually.

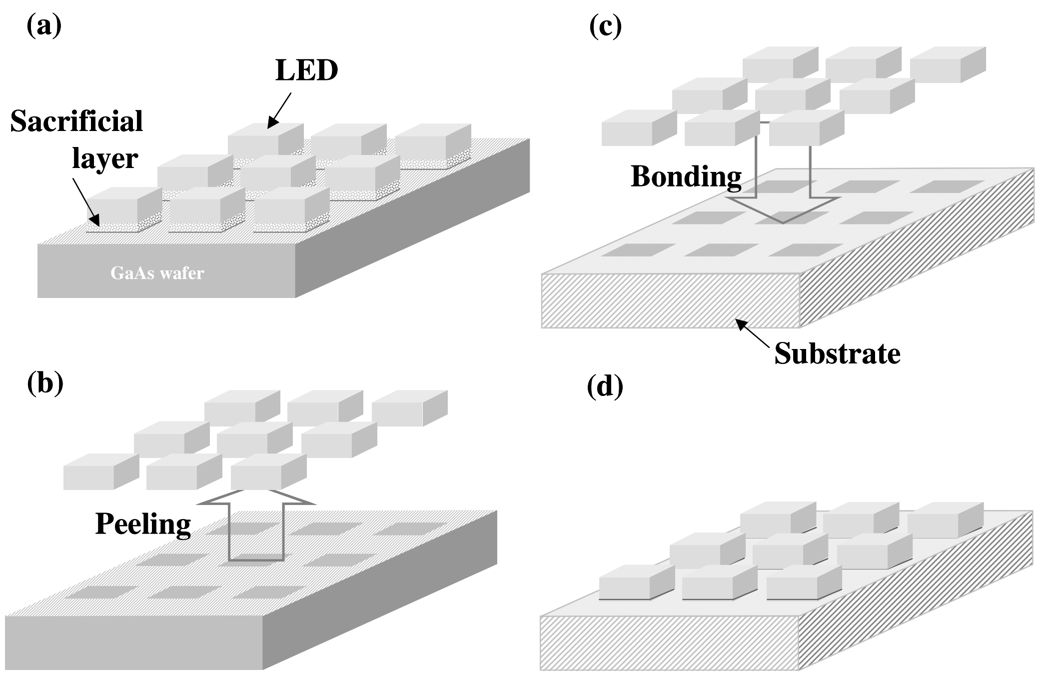

Fig. 5 EFB process outline (process II)

The epitaxial film LEDs are formed on the Si substrate (substrate A), glass substrate (substrate B), plastic substrate (substrate C). Tow types of the epitaxial films are tested to form the two-dimensional LED array. One type of the LED consists of the $Al_xGa_{1-x}A$ epitaxial layers (epitaxial film 1). The active layer of the epitaxial film 1 is designed to emit light of a wavelength of 760nm. Another type of the LED consists of the $(Al_xGa_{1-x})_yIn_{1-y}P$ epitaxial layers (epitaxial film 2). The active layer of the epitaxial film 2 is designed to emit light of a wavelength of 650nm. Both of

Performance of the two-dimensional LED array

LED array on rigid substrates

Figure 6 shows the photograph of the two-dimensional epitaxial film LED array when the LED array displays character. The epitaxial film LED array is formed on the substrate B using the *epifilm 1* by the *fabrication process I.* The epitaxial films are well enough bonded on the substrate to form the two-dimensional LED array. No LED element is released and no crack appears during LED array fabrication process after the epitaxial film bonding process. As shown in Fig. 6, the two dimensional epitaxial film LED array works well.

The two-dimensional epitaxial film LED array fabricated with the *epitaxial film 2* by the *process II* also works well. The two -dimensional epitaxial film LED array can be well peeled off from the GaAs substrate and well bonded on the substrate. No damage and no degradation appear during the peeling process and the bonding process.

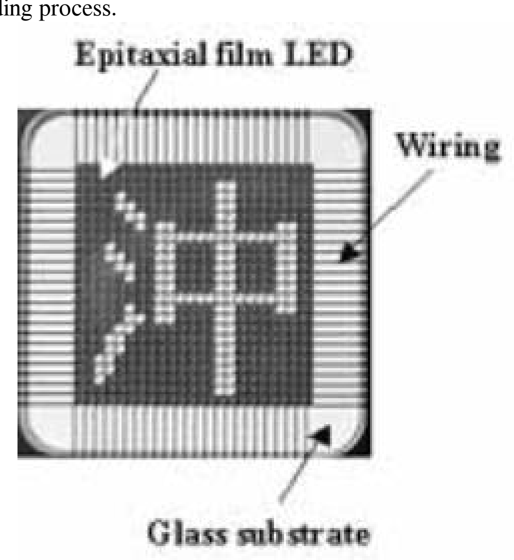

Fig. 6 Two-dimensional epitaxial film LED array on the glass substrate

LED array on flexible substrates

Figure 7(a) shows two-dimensional epitaxial film LED array on the flexible plastic substrate (substrate C, epitaxial film 1, fabrication process II). The epitaxial film of 2µm in thickness is fragile, but flexible. Even when the LED array formed on the flexible substrate is bended as shown in Fig. 7(a), the epitaxial films are not released from the bonded surface and no crack in the epitaxial film appears.

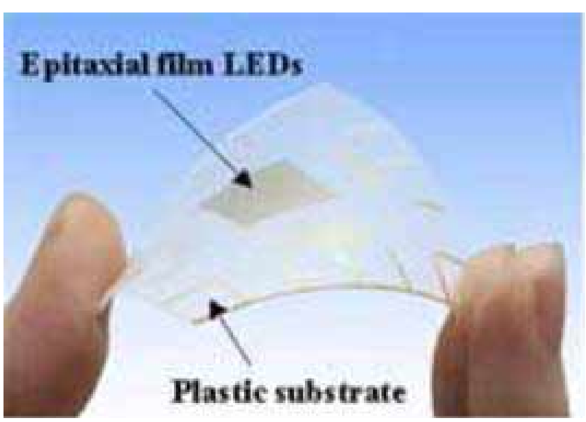

Fig. 7(a) Two-dimensional epitaxial film LED array on the plastic substrate

Figure 7(b) shows the photograph of the two-dimensional epitaxial film LED array on the plastic substrate when the LED array displays character. As shown in Fig. 7(b), the two- dimensional epitaxial film LED array works well on the plastic substrate even when the plastic substrate is bended.

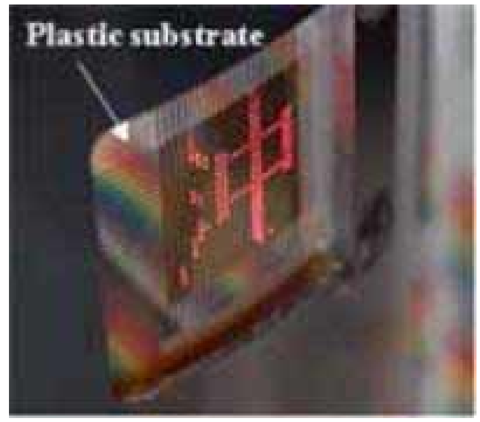

Fig. 7(b) Two-dimensional epitaxial film LED array on the plastic

Higher density two-dimensional LED array

Fabrication of a higher density two-dimensional LED array is tested. Figure 8 shows the photograph of the higher higher density two-dimensional epitaxial film LED array (substrate B, epitaxial film 2, fabrication process II). The size of the one LED is 20µm x 20µm. The pitch of the LED array is 42.3µm in both of x and y directions. The number of the LEDs in the higher density two-dimensional epitaxial film LED array is 24 dots x 24 dots. As shown in Fig. 8, all the LEDs are well bonded on the glass substrate. The two dimensional epitaxial film LED array shown in Fig. 8 works well to display characters.

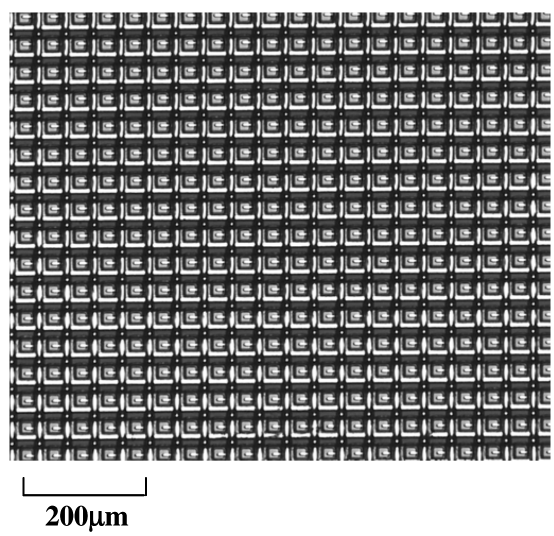

Fig. 8 Higher density two-dimensional epitaxial film LED array

Conclusions

This study demonstrates that the EFB technology provides good fabrication process for integrating dissimilar materials. In this study, two dimensional epitaxial film LED arrays are tested to fabricate on dissimilar material substrates including both of the rigid substrates and the flexible substrates. Two types of the epitaxial film materials are tested (AlGaAs, AlGaInP). In variety of combinations of the substrates, epitaxial film material and fabrication processes, the two dimensional epitaxial film LED arrays show good performances to display characters.

Higher density two-dimensional epitaxial film LED arrays are tested. This study proves that higher density two-dimensional LED array can be transferred to the dissimilar material substrates. The higher density two-dimensional epitaxial film LED array that is bonded on both of the glass substrate and the plastic substrate indicate good performance. The EFB will be one of promising digital fabrication technology and is further developed.

References

[1] M. Ogihara, H. Fujiwara, M. Mutoh, T. Suzuki, T. Igari, T. Sagimori, H. Kurokawa, T. Kaneto, H. Furuta, I. Abiko, and M. Sakuta, "LED array integrated with Si driving circuits for LED printer printhead", Electron. Lett., vol.42, no.15, pp.881-883, 2006.

[2] M. Ogihara, H. Fujiwara, M. Mutoh, T. Suzuki, T. Sagimori, H. Kurokawa, T. Igari, T. Kaneto, H. Furuta, I. Abiko, and M. Sakuta, "New printhead using LED arrays integrated with IC drivers", Proc. 22nd Int. Conf. on Digital Printing Technologies, pp.402-405, Denver, Colorado, Sept. 17-22, 2006.

[3] for example, D. L. Mathine, 'The integration of III-V optoelectronics with silicon circuitry', IEEE J. Select. Topics Quantum Electron., 1997, vol. 3, (3), pp. 952-959

[4] M. Konagai, M. Sugimoto, and K. Takahashi, 'High efficiency GaAs thin film solar cells by peeled film technology', J. Crystal Growth, 1978, 45, pp. 277-280

[5] E. Yablonovitch, T. Gmitter, J. P. Harbison, and R. Bhat, 'Extreme selectivity in the lift-off of epitaxial GaAs films', Appl. Phys. Lett., 1987, 51, (26), pp. 2222-2224

Author Biography

Tomoki Igari received his Bachelor of Engineering in applied physics from the Hokkaido University, Japan (2001) and his Master of Engineering in applied physics from Hokkaido University (2003). Since then he has worked in the Research and Technology Division at Oki Digital Imaging Corporation, Japan. His work has focused on development of epitaxial film bonding technology and LED printheads using this technology.