Wave energy-assisted fluidic self-assembly of LED chips for display applications

Je Jun Ryu, Seong Hyeon Noh, Selim Yun, Chang Wan Park, Seungje Lee, Young Rag Do, and Jae Soo Yoo

School of Chemical Engineering and Materials Science, Chung-Ang University, Seoul, Korea; Department of Applied Chemistry, Kookmin University, Seoul, Korea

ABSTRACT
Micro-light-emitting diode (micro-LED) displays have excellent image characteristics, particularly in terms of contrast ratio, response to electric field, and color expressions. However, these are expensive due to the price of the LED chips. This can be overcome by reducing the size of the LED chip, but the efficiency will decrease as a result. Moreover, the rapid and accurate arrangement of a few million chips with a size of \( \sim 50 \mu m \) to form pixels on the substrate is a challenging task. In this study, fluidic self-assembly process was introduced. The self-assembly design and implementation were limited to building a micro-scale system. With geometric constraints, external forces may influence the outcome of a self-assembled product. In this case, wave energy was used as the external force to manipulate the LED chips on the substrate. Target-generated waveforms in the fluid were used to control the movement of the LED chips. The arrays of the LED chips were arranged on a fine metal mask, i.e. transfer cartridge. The chips were then transferred to a circuit-printed glass plate by face-to-face pressing under high temperature and high pressure. It was found that the wave energy-assisted self-assembly is applicable and beneficial to LED module fabrication.

1. Introduction
Light-emitting diode (LED) has been used extensively as a light source for liquid crystal displays and solid-state lighting since the blue-lighting diode was fabricated on the sapphire substrate [1]. Its excellent optical characteristics, such as high-power efficiency, fast response to electric field, and a wide range of color expressions due to the narrow emitting spectrum, have piqued the interest of display engineers. Meanwhile, Sony Corporation developed and demonstrated the direct application of LED chips to display pixels in crystal LED displays [2]. It showed impressive brightness, blur-free image, wide viewing angle, and excellent contrast. Furthermore, its infinite scalability for video walls of any size or shape is highly sought after in next-generation displays. Lee et al. provided an excellent summary of the LED display technology progress report [3]. Despite the advantages, the challenging issues regarding LED display technology have yet to be resolved. Due to the high chip price and long processing time (long time at completion or TAC), the manufacturing cost may be too high to be accepted in the market. The high chip price can be overcome by reducing the size of the chip. Despite the decrease in chip efficiency with a reduced chip size [4], the rapid and accurate arrangement of a few million chips with a size of at least \( 100 \mu m \) to form the pixels on the substrate is a very challenging task.

Chip arrangement processing includes a transfer assembly. It generally refers to a technology that removes materials, such as various electric devices, patterns, and composites, and transfers them directly onto another substrate. This technology, which is frequently used in semiconductor industries, has the advantage of allowing two-dimensional and three-dimensional structures to be easily stacked and transferred directly onto other substrates, thus bypassing the limitations of photolithography technology. The surface mount technology based on pick-and-place method is a common example of this technology. It is used for high-speed, high-precision placement of a wide range of electronic components, such as capacitors, resistors, and integrated circuits, onto printed circuit boards. By using this technology, various problems of devices manufactured directly on a flexible base material, which were previously difficult to implement as such, have recently been overcome. In the LED display application, LED chips with a size of \( \sim 30 \mu m \)
should be precisely and quickly transferred onto a flexible or flat substrate. Even though this pick-and-place method can minimize the defects in pixels and is also a guaranteed processing method, the situation can be different when it comes to handling the micron-sized LED chips as small as fine dust.

Currently, laser ablation and roll-to-roll transfer methods are being researched. In laser ablation method, laser-induced forward transmission is a process in which a laser beam is used to separate micro-LEDs from a carrier substrate and then transmit them to a receiving substrate. Irradiation with the laser beam causes light material interactions at the interface between the carrier substrate and the die. As a result, the die is separated from the substrate while remaining stuck to the receiving substrate. It can be implemented by using a temporary substrate with a polymeric adhesive that acts as an interfacial layer and decomposes when irradiated with a laser beam. It is capable of transmitting approximately 1000 chips per laser shot. Another method that is being developed by the Korea Institute of Machinery and Materials (KIMM) is the roll-to-roll transfer method. This is a flexible process that can deliver up to 10,000 LED chips per second. The entire process consists of three roll transfer steps. The first step is to pick up and place the control thin film transistor (TFT) array on a temporary substrate by a roll stamp coated with a disposable transfer film. In the second step, the micro-LED is lifted from the supporting substrate, placed on a temporary substrate, and connected with the TFT via solder bonding. In the final step, an array of interconnected micro-LEDs and TFTs is roll-transferred onto a target substrate in order to form an active matrix micro-LED display.

However, as previously mentioned, the key factors in the transfer assembly are precision and speed. To construct the direct pixel out of the LED chips, the LED chips must be smaller than ∼50 μm in size, and more than 24 million chips are transferred for the 4K (3840 × 2160) resolution display. In this case, a more innovative approach is necessary. An orientation-controlled alignment process was recently introduced, thus leading to the development of a quantum nanorod light-emitting display [5]. In this study, we used the fluidic self-assembly method for rearranging the LED chips. The semiconductor industry is well-positioned to take advantage of even micro-scale self-assembly techniques [6]. The design and implementation of these self-assembly techniques are limited to the construction of micro-scale systems. External forces and geometric constraints can control the outcome of a self-assembled product. Gravity and hydrodynamic forces can be used to guide the LED chips into recesses on a substrate.

The use of capillary forces to guide the self-assembly of LED chips onto binding sites has produced very promising results [7]. In this work, wave energy is used as an external force in order to manipulate the LED chips on the substrate. Furthermore, the wave energy-assisted self-assembly sieving technique is demonstrated by accurately and effectively placing the LED chips at the target position of the substrate.

2. Experimental methods

In fluidic self-assembly, freestanding microcomponents were introduced over a template by fluid drag and allowed to spontaneously assemble in a binding site of which the template is correspondingly patterned. For instance, Saeedi et al. fabricated the circular (320 μm diameter) LED chips and prepared the 100 μm thick clear polyethylene terephthalate (PET) template separately [8]. In the template, the metal interconnects and pads in the receptor sites were defined. Subsequently, the template was submerged in a warm acid liquid. In this case, self-assembly occurs as μ-LED chips first fall into complementary receptor sites and become bound by the capillary force resulting from a molten alloy. During the self-assembly, the μ-LEDs gently moved across the template surface influenced by gravity, by shaking, and by the fluid flow generated by tilting and with a pipette. When the μ-LEDs came into contact with molten alloy, the metal pads became wet, thus forming a strong bond between the μ-LEDs and the metal alloy. They reported that correctly assembling the μ-LEDs and forming electrical connections achieved a 62% yield [8]. For display applications, a 100% yield has to be achieved, and it should be noted that the incorrect permanent contact between the μ-LED and the metal can result in serious rework problems. We tried to control the motion of the μ-LED chips more precisely in our self-assembly by using the waveform in the fluid, which minimizes fluid drag. Only gravity and wave energy were dominant in our experimental setup when we used relatively large-sized LED chips. The schematic diagram of the experimental apparatus is shown in Figure 1(a), and the LED flip chips (Sanan product) used in the experiment is shown in Figure 1(b). The LED flip-chip is composed of gallium nitride (GaN), which is used for blue LEDs, and two electrode pads. The experimental apparatus is composed of a fine metal mask (Figure 1) with the LED chips on the top surface, wave form generator, and its driving computer. The metal template was patterned to accommodate the LED chips on the top surface and was tightened by the aluminum chuck. Here, the LED chips were manipulated by the acoustic wave. The shape of the aluminum chuck is significant because it determines the wave form, which will be discussed in more detail. The frequency and the
amplitude of the wave were controlled by the function generator with a tablet PC. Figure 1 shows the schematic of the experimental apparatus.

3. Results and discussion

In self-assembly, force manipulation is important, and various assembly techniques have been developed. A fluidic process based on gravitational and shear forces has been used to assemble gallium arsenide (GaAs) LEDs onto silicon, and silicon electronics onto glass for flat panel displays [9]. Tens of thousands of LED chips per minute were reported to have been assembled with ±1 μm. However, gravitational force was relatively weak compared to the restoring and adhesion forces. In addition, the fluid drag was not good enough to control the chips moving onto the template. In our technique, we used wave energy as the external force. The idea of chips moving onto solid surface via wave energy dates back to the eighteenth century, when Ernst Chladni reported the detailed studies on the aggregation of sand onto the nodal lines of a vibrating plate, also known as the Chladni plate [10]. The acoustic field can be represented in two dimensions as a rectangular cavity by the superposition of two orthogonal standing waves, and the pressure distribution in the chamber can be approximated as

$$p_{in}(r|r_1) = \frac{p_0}{2} \{e \cos[k(x + x_1)] + \cos[k(y + y_1)]\}$$

where \(p_0\) is the pressure magnitude, \(e\) is the dimensionless amplitude of the standing wave along the x axis, \(k = 2\pi/\lambda\) is the wave number, and \(r_1 = x_1 + y_1\) is the distance from the particle to the antinode at \(x = 0\) and \(z = 0\) [11]. If small-sized LED chips are dropped in this field, the chips move according to the force acting on the LED chips and become trapped at certain points where the acoustic radiation force is zero (potential well). In our experiments, the chip theoretically moved along the clamped rectangular Chladni pattern. We calculated the Chladni patterns in order to have a better understanding of the behavior of the chips. This pattern is based on the wave number, and the simulated patterns are shown in Figure 2.

In our experimental setup, the acoustic waves were generated in a three-dimensional chamber with a rectangular base (20 × 30 × 2 mm). The chamber height was much smaller than the other orthogonal dimensions. Figure 3 shows various wave patterns according to the given frequency below the chamber of our experimental setup.

At this point, we could control the motion of the LED chips on the template in a chamber by repeatedly adjusting the frequency with the proper amplitude. The template was then designed and fabricated. The template for transporting the LED chips onto the printed circuit board was loaded properly on the chamber, and the experiments were carried out. The hole size on the template is 120 × 120 μm square, which is 120% longer than the LED flip chips (100 × 100 μm), and the pixel pitch is 680 μm. Since its thickness is 70 μm, the LED flip chips can be placed perfectly in a template hole, and only 40 chips were missed. In the experiment, we could see the chips moving from the center to the edge of the chamber. They formed a circular line and appeared to grow in size. The chips fell into the holes during this one-way movement. There were 1392 holes (48 × 29 ea), and Figure 4(a) shows the arrangement of 1352 chips (97% of the holes). Almost every chip is properly positioned in a single shot. Figure 4(b) shows in detail how the LED flip chips dropped into the holes of the template.

The LED flip chips transferred to the template were now bonded to the circuit board by anisotropic conductive film (ACF), which is made by mixing fine conductive particles with adhesive resin (generally thermosetting). The general process, including the ACF flip-chip bonding condition, was described in detail. To check process feasibility, a glass board was designed and fabricated in
Figure 2. Simulation of four patterns according to the wave number $k$ shown with color gradient (left) and simple gradient (right) of (a) $k = 6.42$ Hz, (b) $k = 11.6$ Hz, (c) $k = 40.03$ Hz, and (d) $k = 63.11$ Hz.

Figure 3. Various wave patterns according to the given frequency in a chamber of experimental set-up: (a) 78 Hz, (b) 108 Hz, (c) 181 Hz, and (d) 284 Hz.

the Advanced Display Research Center, Kyung Hee University. Figure 5(a) shows an $8 \times 8$ pixel array. Each pixel design has a cathode pad and an anode pad, as shown in Figure 5(b). They are connected to the chip’s electrode pads. It should be noted that this simple design is for process validity.

We used thermosonic to check the feasibility of the ACF bonding process. The first and most important step is to achieve a successful alignment between the chip and the circuit board. The precision with which the LED chips are positioned is also important. The ACF equipment includes a camera and a moving stage for adjusting the position in detail. The pressure, heat, and ultrasonic waves were subsequently applied on the chips, board, and epoxy resin film. Since resin contains conductive particles, such as nickel (Ni), a conductive path between the electrodes is created [12]. In a fine pitch process, this can reduce the time for bonding the chips on the panel.
4. Conclusion

In this study, wave energy-assisted self-assembly was confirmed for arranging LED chips in pixel form. It was found that the two-dimensional excitation field formed by the vibration and amplitude values on the transfer plate was converted to kinetic energy through the medium and controlled behavior of the mini-LED chips. Accordingly, it was confirmed that the optimum frequency was determined experimentally. This process showed the possibility of mass transfer of micro-LEDs in a short period of time. The potential advantage of this process is that LED binning can be conveniently done on defective devices before module fabrication.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) [grant number 2021R1F1A1060473]. This research was supported by the Chung-Ang University Research Scholarship Grants in 2021.

Notes on contributors

Jejun Ryu received his B.S. degree in applied chemical engineering from Chung-Ang University in Seoul, Korea in 2020. He worked as a researcher in the Display Materials Lab. The main research topic was micro-LED display manufacturing process for its panels and modules. His research can be found at IMID 2021, where he won the prize. He is currently working as a researcher at the KOLON, a Korean company.

Seonghyeon Noh received his B.S. degree in applied chemical engineering from Chung-Ang University in Seoul, Korea in 2021. He is currently working towards his M.S. degree in chemical engineering at Chung-Ang University. His research interests include micro-LED transfer and display device development.

Selim Yun received her B.S. degree in applied chemistry from Kookmin University in Seoul, Korea in 2020 and her M.S. degree in chemistry from Kookmin University in 2022. Her research interests include the development of ultra-small and ultra-thin LED materials, as well as process and display device development.
Changwan Park received his B.S. degree in applied chemical engineering from Chung-Ang University in Seoul, Korea in 2021. He is currently working towards his M.S. degree in chemical engineering at Chung-Ang University. His research interests include micro-LED transfer and display device development.

Seungje Lee received his B.S. degree in applied chemistry from Kookmin University in Seoul, Korea in 2019 and his M.S. degree in chemistry from Kookmin University in 2021. He is currently working towards his Ph.D. degree in chemistry at Kookmin University. His research interests include ultra-small and ultra-thin LED materials, as well as process and display device development.

Youngrag Do has been a professor at Kookmin University since 2004. He received his bachelor’s and master’s degrees from the Department of Chemistry at Korea University in 1986 and 1988, respectively. He received his Ph.D. in solid chemistry from Brown University in 1994. From 1993 to 2004, he served as a senior researcher and chief researcher at Samsung SDI’s corporate research institute. His research interests include ultra-small and ultra-thin LED materials, process and display device, quantum dots, luminescent materials, photonic crystals, dichroic optical filters, nanopattern fabrication, and optoelectronic device applications.

Jaeseo Yoo joined Chung-Ang University at 1994. He received his bachelor’s degree from the Department of Chemical Engineering at Seoul National University in 1982 and his Ph.D. from the University of Florida in 1991. He developed a high-power semiconductor laser for signal processing at Samsung Advanced Institute of Technology from 1991 to 1994. At Chung-Ang University, he has been working on phosphor synthesis and characterization for display application. He is currently very interested in the application of acoustic sound energy to the manufacturing process of ICT.

ORCID
Young Rag Do (http://orcid.org/0000-0002-0580-4628

References

[1] D. Feezell, and S. Nakamura, C. R. Physique 19, 113 (2018).
[2] G. Biwa, M. Doi, A. Yasuda, and H. Kadota, Dig. Tech. Pap 50, 121 (2019).
[3] H.E. Lee, J.H. Shin, J.H. Park, S.K. Hong, S.H. Park, S.H. Lee, J.H. Lee, I.S. Kang, and K.J. Lee, Adv. Funct. Mater 29, 1808075 (2019).
[4] E.-L. Hsiang, Z. He, Y. Huang, F. Gou, Y.-F. Lan, and S.-T. Wu, Crystals 10, 494 (2020).
[5] Y.J. Eo, G.Y. Yoo, H. Kang, Y.K. Lee, C.S. Kim, J.H. Oh, K.N. Lee, W. Kim, and Y.R. Do, ACS Appl. Mater. Interfaces 9, 37912 (2017).
[6] W. Lu, and A.M. Sastry, IEEE Trans. Semicond. Manuf 20, 421 (2007).
[7] U. Srinivasan, D. Liepmann, and R.T. Howe, J. Microelectromech. Syst 10, 17 (2001).
[8] E. Saeedi, S. Kim, and B.A. Parviz, J. Micromech. Microeng 18, 075019 (2008).
[9] H.-J.J. Yeh, and J.S. Smith, IEEE Photonics Technol. Lett 6, 706 (1994).
[10] P.H. Tuan, C.P. Wen, P.Y. Chiang, Y.T. Yu, H.C. Liang, K.F. Huang, and Y.F. Chen, J. Acoust. Soc. Am 137, 2113 (2015).
[11] G.T. Silva, J.H. Lopes, J.P. Leão-Neto, M.K. Nichols, and B.W. Drinkwater, Phys. Rev. Appl 11, 054044–1 (2019).
[12] Y. Song, B.S. Yim, J.S. Joung, and J.M. Kim, Journal of KWJS 29, 25 (2011).