Inkjet Printing for Optical/Electrical Interfacing of VCSEL and PD Arrays

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Abstract

Vertical cavity surface emitting laser (VCSEL) arrays and photodiode (PD) arrays have emerged on the market for short reach fiber communications and other applications. However, the lack of efficient, low-cost methods for light coupling and electrical connection has become a barrier to new products incorporating their high-density and parallel advantages. To address these challenges, we have developed a wafer-level integration of micro-optics with VCSEL array and a direct 90° solder bonding of linear array die. The micro-optic structure consists of a cylindrical pedestal processed by very-thick film coating-patterning and a microlens fabricated on top of the pedestal by pre-polymer printing. The alignment of pedestal to VCSEL is ensured within the photolithographic process, and that of microlens to pedestal has a self-centering nature. The solder bonding, which connects the bond pads on VCSEL/PD array with the metal leads on substrate, is accomplished by molten solder printing. The test results on the fabricated parts demonstrated that the micro-optic structure improves the coupling efficiency from VCSEL to multimode optical fiber, while not altering the VCSEL’s emission characteristics. Also, the solder printing is compatible with these optoelectronic devices by the direct applicability and by not altering the emission characteristics or the responsivity of the dies. Because of the wafer-level processing, the new interfacing method offers both technical advantage and cost-effectiveness for manufacturing.

Key words: inkjet printing, VCSEL array, PD array, micro-optics, solder bonding, wafer-level integration.

1. Introduction

VCSELs have been well recognized as low cost light sources for fiber optic interconnects. They have also found numerous applications in free space interconnects, detection sensors, position sensors, scanners, etc. VCSELs are fabricated in a monolithic process. Because the light beam is emitted perpendicular to the surface, VCSELs are tested at wafer-level. One dimensional and two dimensional arrays can be diced from wafers directly. PDs have been fundamental light detection devices. They are paired with VCSELs for high speed data communication. They are also widely used in other light detection instrumentations. Almost all applications of these photonic devices require the presence of micro-optics to collimate or converge the emitting or receiving light beam to increase optical coupling efficiency. For this purpose, ball lenses and V-grooves have been used to collimate or converge single VCSEL’s beam. These structures are difficult to implement to the VCSEL arrays which are normally 250 µm × 250 µm per unit in today’s industrial standard. Currently, a typical optical interfacing for 850 nm VCSEL array consists of a spacer and a microlens array. The space between the VCSEL emitting facet and the microlens array is necessary for optical performance and also for wire bonding. This seemingly simple structure is actually rather demanding in engineering. Even for multimode applications, all parts are pre-fabricated with the accuracy of 1-2 µm and then all the parts have to be aligned and bonded with an accuracy of about 2-5 µm. The trend in miniaturization and integration with electronic circuits makes these interfaces even more challenging. Although significant efforts have been made in the past years to integrate large scale VCSEL array with micro-optics and silicon CMOS circuits, the packaging and assembly still remain as key factors for the continuing success in photonic industry. To address these pressing needs, we have developed a wafer-level integration of micro-optics and chip-level die bonding by inkjet printing of picoliter volumes of optical epoxy and molten solder to form the interfacing structures. The inkjet technology is accurate, flexible, data-driven, and low cost.

2. Concepts and Designs

Optical interface: As shown in Fig. 1, the laser emission can be modeled as from a virtual point source
behind the emitting facet and with Gaussian intensity distribution. A transparent pedestal is fabricated directly on VCSEL and a microlens is fabricated on top of the pedestal. The resulting beam shape is decided by the selection of the dimensions of micro-optic structures, and the indices of refraction of the materials. For an effective coupling from VCSEL to graded-index multimode fiber (MMF), a ray tracing gives typical pedestal diameter (also microlens diameter) in the range of 100 - 120 \( \mu m \); pedestal height in the range of 70 - 120 \( \mu m \); and lens height in the range of 30 - 40 \( \mu m \). The coupling from MMF to PD is less critical than that from VCSEL to MMF, due to the relatively large active area of PD. The ray tracing, shown in Fig. 2, gives typical pedestal diameter in the range of 100 - 120 \( \mu m \); pedestal height in the range of 40 - 80 \( \mu m \); and lens height in the range of 30 - 40 \( \mu m \). The models used here may not present the real conditions of the parts involved. Nevertheless, the results provide a guideline to the process development.

**Electrical interface:** As shown in Fig. 3, the VCSEL- or PD-array die is placed and temporary bonded to the substrate in a geometry that the active surface is perpendicular to the substrate. This workpiece is then placed under the solder jet printhead with a certain tilt angle. The printed solder balls will connect the bond pads on the VCSEL/PD side with the leads on the substrate side. 1x4 multimode VCSEL die and 1×4 PD die are selected for this demonstration. The 1×4 die has the dimensions of 0.25 mm × 0.25 mm × 1 mm. A test coupon with Au leads is the substrate.

### 3. Processes

There are 3 key tasks in the process development for achieving the design goals: very-thick film coating and patterning for pedestals, microlens printing on pedestals, and solder ball printing on 90° joint.

**Very-thick film patterning for pedestals:** Photosensitive polymer materials with high glass transition temperature, high thermal stability, and high optical transparency were selected as candidates. The conventional photolithographic process was used to pattern the very-thick film to form the pedestals. The alignment from pedestal to VCSEL is ensured in the photolithographic process and the alignment from microlens to pedestal has a self-centering nature. The mechanical stability (the strength of pedestal and the adhesion of pedestal to the substrate) is also considered in the process development.

**Inkjet printing of microlenses**\(^7,8\): The microlens material, MRXH series, is an in-house developed 100% - solid (solvent free) formulation of pre-polymer. Its viscosity is reduced to below 40 cps by elevating the printhead temperature to 100 °C. The curing procedure ensures a full polymerization. The main control parameter during printing is the number of polymer drops dispensed on top of each pedestal. Due to the small size of microlens, small drop size is desired. For this purpose, small jetting nozzles are used and other jetting parameters are adjusted to have drop diameter about 40 \( \mu m \). The polymer printhead is shown in Fig. 4.

**Inkjet printing of solder balls**\(^9\): In addition to using adhesives for the temporary die bond, we explored also the design and fabrication of MEMS clamper for holding the dies in position. The clamper is made of electroplated Ni. Its position and dimension are controlled in the photolithographic process with an accuracy of ±1-2 \( \mu m \). This clamper provides also a
self-alignment of the die to other features constructed on the substrate. No further adjustment is necessary once the die is placed. The die-coupon unit is then placed under the printhead with a certain tilt angle. The alignment of printhead with the workpiece is critical due to the small dimensions. The printhead (piezoelectric jetting device and liquid solder reservoir) is operated at temperatures above 200 °C for eutectic 63Sn/37Pb alloy. A N₂ co-flow is applied at the dispensing nozzle to prevent the molten solder from oxidation. Contrary to the polymer printing of microlens, here large drop size is desired. By using a saw-tooth waveform with long rise time under software control, the drop size can reach 100 - 105 µm for single ball per site bonding. The solder printhead is shown in Fig. 5.

4. Results and Test Data

Pedestals and micro-lenses fabricated directly on VCSEL wafer: Fig. 6 shows a pedestal-micro-lens array on a VCSEL wafer. The pedestals have uniform, clean finishing with vertical side walls. The bond pads, which appear as circular features on the wafer surface, are well exposed after the process. The micro-lenses were printed with different lens heights for evaluation. The processed wafer was then diced into arrays. The micro-optic structures are intact in the harsh dicing environment. Fig. 7 shows a diced VCSEL array positioned by a pair of nickle grippers. The right-most pedestal (no micro-lens printed) retains its partial structure even if it was cut through by the dicing blade. This gives an evidence of the mechanical strength of the pedestal and its adhesion to the GaAs substrate.

The optical performance of the micro-optics was evaluated by the coupling efficiency from VCSEL to 50/125 MMF. The coupled power was measured at varying axial distances from the VCSEL’s emitting facet to the fiber tip for a series of lens heights, as shown in Fig. 8. Here the coupling efficiency is the ratio of the power collected by the MMF to the power collected by a large-area silicon detector placed closely to the lensed VCSEL. Butt coupling is also presented for comparison. All pedestals on the same wafer have
the same dimensions: diameter 115 µm and height 100 µm. The drop diameter of the epoxy is 43 µm. The control parameter \(N\) is the drop number of epoxy dispensed. \(N=0\) is related to the pedestal-only case. \(N=3\) – 7 result in a series of lens heights of 25, 28, 33, 36, and 38 µm, respectively. The curves in Fig. 8 show the improvement of the coupling efficiency. For example, when the axial distance is 0.6 mm, the coupling efficiency can reach 0.6 for \(N=6\), rather than 0.3 of butt coupling. Note that it was not our intention to compare the coupling data with ray tracing directly, because the VCSELs on the processed wafer have a beam profile deviated from Gaussian. Also, the reflection loss was not considered in this analysis.

To assess the compatibility of the micro-optics process with the finished VCSEL wafer, we measured VCSEL emission characteristics, forward voltage versus current and emitting power versus current, in 3 cases: before any process (as a baseline); after pedestal was fabricated; and after pedestal-microlens was fabricated. The assessment was performed on a comparative base. The data shown in Fig. 9 indicate that the diverging of the test data for these 3 cases does not exceed that of the baseline VCSELs. It is reasonable to say that the DC properties of VCSELs are not altered by the additional process for fabricating micro-optics.

90° solder bonding of VCSEL- and PD-array dies to substrate: Solder bonding was performed on a solder jet platform at MicroFab. Fig. 10 shows the bonding of a 1×4 VCSEL die to a test coupon. Fig. 11 shows the bonding of a 1×4 PD die to a test coupon. The 4 solder balls connect the anode bond pads on the die with the metal leads on the coupon, and one or more solder balls connect the cathode metallization on the back side of the die with the lead on the coupon.

To assess the compatibility of solder bonding with GaAs wafer, the VCSEL’s emission characteristics, forward voltage versus current and emitting power versus current, and the PD’s responsivity were measured. The results for before and after solder bonding are given in Figures 12, 13, respectively. It is seen that the solder bonding does not have an obvious effect on altering these characteristics.

Fig. 8. Coupling efficiency from VCSEL to MMF for different epoxy drop number \(N\) printed on pedestals to form microlenses. Parameters are given in the text.

Fig. 9. DC characteristics of VCSELs: dashed lines - baseline VCSELs; open circles - VCSELs with pedestals; cross marks - VCSELs with pedestals and microlenses.

Fig. 10. 90° VCSEL die bonding by using solder jet.

Fig. 11. 90° PD die bonding by using solder jet.
5. Conclusions and Discussions

The integration of micro-optics presented in this paper is performed at wafer level. After a VCSEL wafer is processed with pedestals and microlenses, sub-optical assembly can be diced in single units or in 1D and 2D arrays with any sizes. This manufacturing method provides high performance, high throughput, and low cost. This method can also be used for the integration of discrete parts in other micro-optic assemblies. The solder bonding of 1D die to PCB presented in this paper can be applied to the chip-level bonding, i.e. to bond the GaAs die directly onto silicon CMOS circuits. In some other situations, for example, the read-write hard-disk where the spatial constrain hinders wire bonding, this method can be a unique solution to handle the electrical interconnect. Future works will be focused on design optimization, reliability, and comprehensive tests.

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References


