

# New Packaging Technology for 2-dimensional VCSEL Arrays and Their Electro-Optical Performance and Applications

Rainer Dohle, Senior Member, IEEE\*, Christian Neumeyr\*\*, Maximilian Wallrodt\*,  
Gerold Henning\*, Thomas Friedrich\*, Christoph Gréus\*\*, Jürgen Roskopf\*\*, Robert Hohenleitner\*\*  
Micro Systems Engineering GmbH\*  
Schlegelweg 17  
Berg, Bavaria, 95180, Germany  
VERTILAS GmbH\*\*  
Daimlerstr. 11d  
Garching, Bavaria, 85748, Germany  
Ph: +49 9293 78-717; Fax: +49 9293 78-41  
Email: rainer.dohle@mst.com

---

## Abstract

At IMAPS2021, we reported on 1-dimensional VCSEL arrays and the packaging technology developed for these arrays, but this time we present the manufacturing workflow and look at the challenges presented by the packaging of special long-wavelength 2-dimensional vertical-cavity surface-emitting laser (VCSEL) arrays in various dimensions. We will show that available packaging technologies for epoxy application by silk screening, die- and wire bonding can be adapted for the unique properties of the 2D VCSEL arrays, delivering high accuracy for production with great overall yield. Proof of the excellent reliability and lifetime will be given through mechanical and electro-optical testing results. The technologies developed for 2D laser arrays will enable new devices for various new applications like high channel count interconnects for data communication and high power VCSEL solutions for 3D sensing.

The perfected wire bonding process secured a homogeneous monometallic structure of the wire bonds, a reduced, well defined bond loop height, with sufficient clearance of the bonding wire above the VCSEL surface. Properly set-up manufacturing procedures for the packaging of the VCSEL arrays are necessary to achieve high performance and reliability of the products presented. Processing of large 2D-VCSEL arrays will be part of the paper.

2D arrays have enabled VCSEL technologies to address a wide range of new laser-based sensing applications. VCSEL products vary from laser chips with only a few emitters for proximity sensors up to several thousands of emitters for LiDAR systems. Applications include systems for the automotive, industrial, medical and consumer markets. There is a strong and growing market opportunity for long wavelengths VCSELs, e.g. based on InP material enabling single mode and multi-mode 2D-VCSEL arrays from 1.3 to beyond 2  $\mu\text{m}$ .

For 3D sensing systems and free-space optical communication, long wavelength 2D-VCSEL arrays offer improved eye safety and further benefits. The long wavelength VCSELs discussed in this paper can be deployed in a wide range of sensing and optical communication applications.

## Key words

2-dimensional VCSEL arrays, applications, electro-optical performance, high reliability, packaging technology, SSB, wedge-wedge bonding

---

## I. Introduction

VCSEL arrays have a very broad application potential [1]. We published our packaging technology for single long-wavelength VCSELs and our packaging technology for 1D VCSEL arrays [2-3]. The objective of this paper is the development of an assembly technology for 2D VCSEL

arrays with high positioning accuracy, using gold-based conductive glue, securing high yield and obtaining extremely high reliability. For highest reliability, gold wire bonding of the top side contact of the VCSEL to a substrate with gold metallization has been a customer requirement. That means a monometallic contact system has been used.

## II. VCSEL Array Design

The 2D VCSEL arrays reported in this paper consist of 12 to 800 emitters. Fig. 1 shows an example:

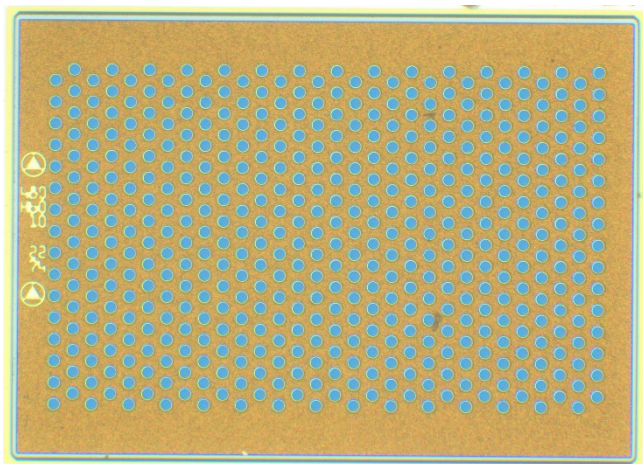


Figure 1: VERTILAS 2D VCSEL array with 480 emitters

Fig. 2 shows a schematic cross section of 2D VCSEL arrays from VERTILAS:

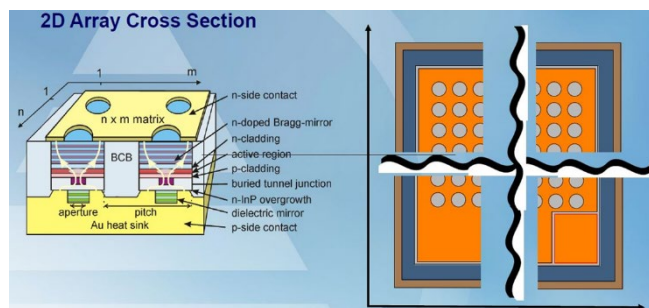


Figure 2: Schematic of a 2D InP VCSEL array structure from VERTILAS (BCB=Benzo Cyclo Butene)

One of the unique features of these VERTILAS laser arrays is the galvanic gold substrate structure at the bottom acting as an integrated heat spreader and heat sink. The BCB reduces parasitics and enables superior HF properties.

## III. Screen Printing

The required thickness of the conductive glue of about 45 microns presupposed the development of a non-standard printing process. We used a special nano coated screen VA 200-0.036D-22.5° with MS50μm film and surface coating. Screen printing is, to our point of view, due to better printing quality for this glue thickness, the preferred technique for large area printing of conductive glue.

## IV. Stencil Printing

Another possibility for the printing of the conductive glue is

stencil printing with a nanocoated stencil, preferably for a glue thickness of 50 μm or higher. If a lower glue thickness is required, the resulting low stencil thickness leads to a short live time of the stencil and screen printing tends to result in lower total costs in that case. In addition to that, we observed occasionally smearing of the conductive glue during stencil printing if the stencil is not cleaned very often. Stencil cleaning reduces productivity, however. On these grounds screen printing has been chosen for manufacturing.

## V. Die Bonding

For the die bonding of thin, fragile III-V semiconductor chips, unique process parameters and processing tools were developed.

In [4] are key properties for die pickup of ultra-thin silicon dies from a wafer foil described: die strength (or fracture strength), bending stress during pickup, edge peel force and bulk peel force. Because the III-V semiconductor material is much more fragile than Silicon and has a lower die strength than Silicon semiconductors, the die pickup from the wafer foil is even more difficult. The peeling of the dies from the wafer tape during die bonding is a very critical process because die stress levels during peeling are significantly high [4]. The thinner the die, the higher the stress [4]. For the separation of the wafer foil from the VCSEL array, a certain peel energy  $G$  is needed. Very important is a low peeling speed  $v$  due to the relation:

$$v = \alpha \left[ \frac{G}{\beta} \right]^3 + v_0 \quad [4] \quad (1)$$

$\alpha=0.08$  mm/s,  $\beta=1$  J/mm<sup>2</sup>,  $v_0=3.2$  mm/s. For  $G<1$  J/mm<sup>2</sup>, the peel front will not proliferate, however [4]. The speed of the moving ejector parts that activate the peeling process had to be optimized to get acceptable results.

The wafer dicing method has not only an impact on die strength, but also the adhesion of the die curbs on the wafer foil [4]. Due to the thick Gold backside metallization, the wafer dicing process is critical, as well as a wafer foil with low peel force. The temperature has only a secondary effect on peel force and die pick-up is therefore not discussed in this paper. Fig. 3 shows the die pick-up from the blue Mylar tape with the used die bonding machine:

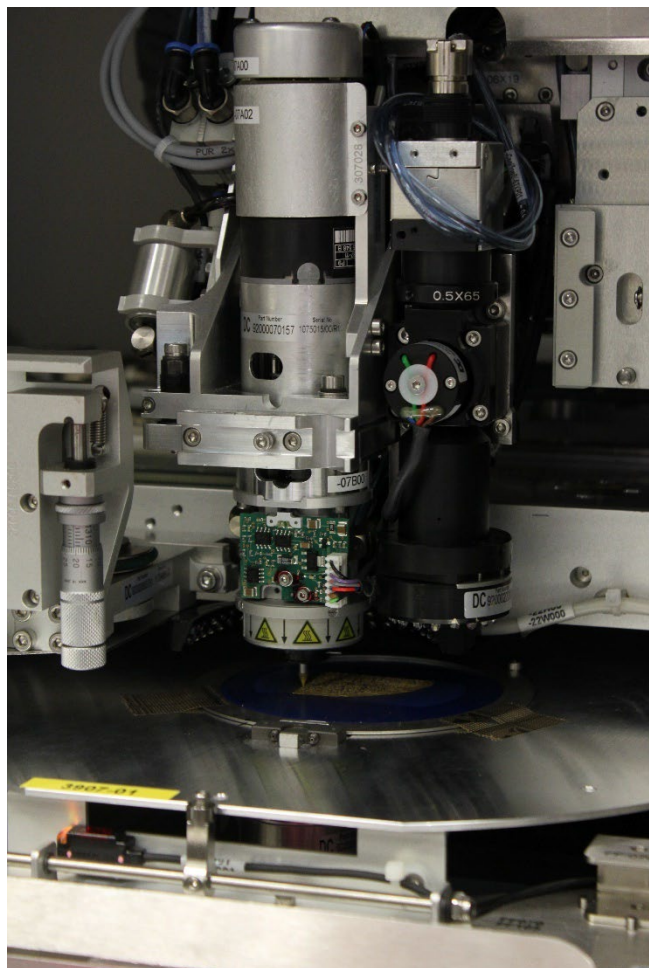


Figure 3: Pick-up from the wafer foil

## VI. Wire Bonding

### A. Wedge-Wedge Bonding

One possibility we explored is wedge-wedge bonding of the 2D VCSEL arrays using Gold wire. We bonded from the substrate (first bond) to the VCSEL array (second bond). The number of the required bonding wires depends from the maximum current (see chapter VII) and the current carrying capacity of the used bonding wire, which can be found in the literature.

Fig. 4 shows a wedge-wedge bonded 2D VCSEL array with 800 emitters using Gold bonding wires with 25  $\mu\text{m}$  diameter, fig. 5 a 312 emitter 2D VCSEL array with 25  $\mu\text{m}$  Gold bonding wire showing the loop and the wedge geometry.

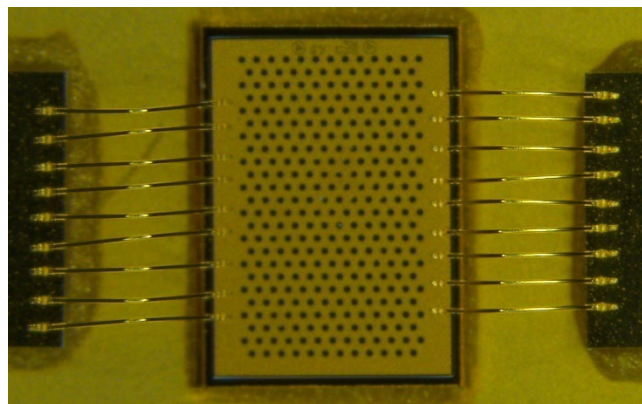


Figure 4: Wedge-wedge bonded 2D VCSEL array with 300 emitters die size 1.86mm by 1.36mm

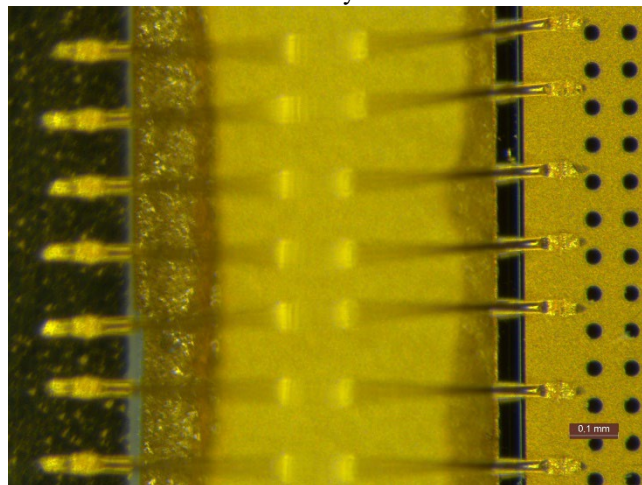


Figure 5: 312 emitter 2D VCSEL array with 25  $\mu\text{m}$  Au bonding wires showing the loop and the wedge geometry

### B. Stand-Off Stitch Bonding

Stand-Off Stitch bonding (SSB) involves the placement of a ball bump at one end of the wire interconnect, then placing a wire with another ball at the other end of the interconnect and stitching off the wire on the previous placed ball bump. This results in a near homogeneous stitch bond interconnect to the bump with an inherent improvement in stitch bond pull strength. The SSB process allows a finer control of bump height and flatness and a reduced overall height (non-compressed about three times of the wire diameter).

Stand-Off Stitch bonding has been performed at a bonding table temperature of 125°C or below. The ball is pressed to the bonding pad on the die with sufficient force to cause plastic deformation and atomic interdiffusion of the wire and the underlying metallization, which ensures the intimate contact between the two metal surfaces and forms the first bond. The loop geometry has been optimized to keep enough distance to the edge of the die. A nondestructive pull-test was carried out on some samples to ensure that the wires are stable and reliably connected.



More details regarding SSB bonding can be found in our previous work [21].

Fig. 6 to fig. 9 show 2D VCSEL arrays with SSB bonds:

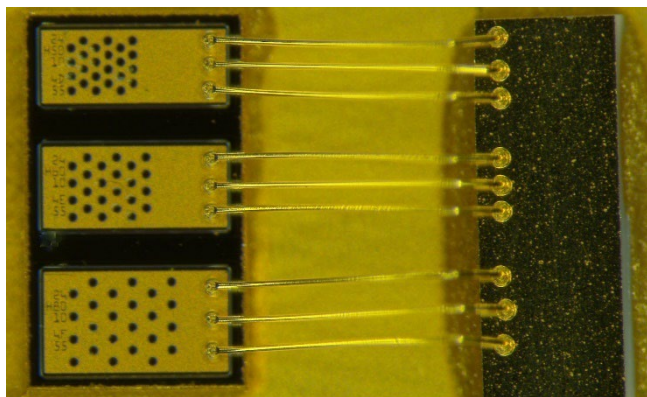


Figure 6: 2D VCSEL arrays with 20 μm Au bonding wires

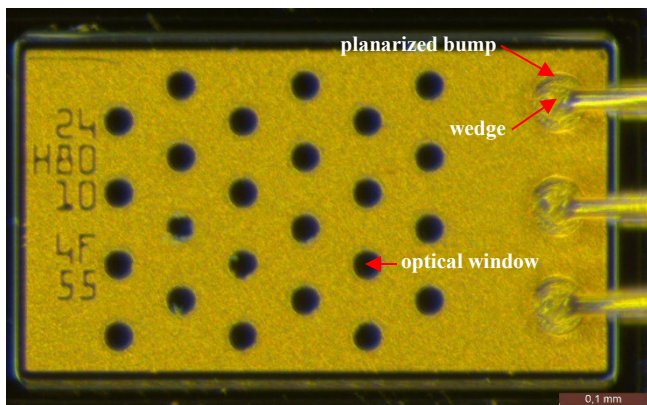


Figure 7: 24 emitter 2D VCSEL array with SSB bonds

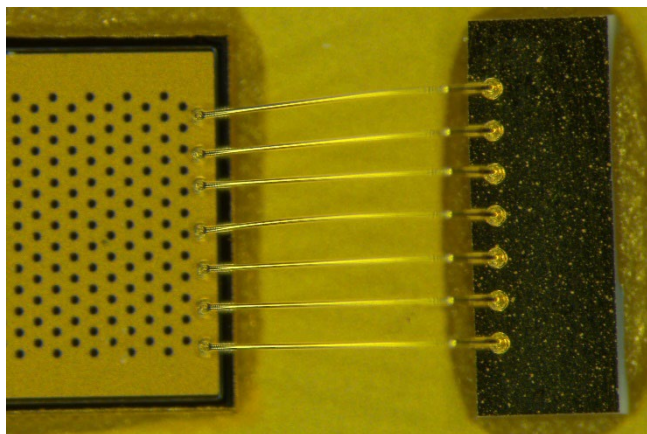


Figure 8: 312 emitter 2D VCSEL array with Au bonding wires with 20 μm diameter

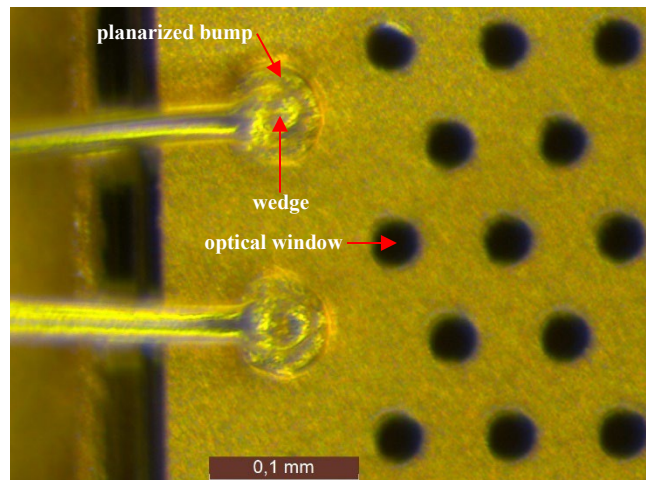


Figure 9: Detailed view of two of the SSB bonds

The decision regarding wedge-wedge-bonding or SSB bonding depends mainly from the required loop geometry.

## VII. Burn-In

For InP based VCSEL arrays, a burn-in process on component level is required. The lasers are being stressed with temperature and current over a certain period. It ensures that the laser parameters remain stable or show only a small change within certain tolerances during operation over many years. The lasers are being characterized by electro-optical testing before and after the burn-in step. This includes measuring the optical power and voltage over current characteristics, as well as optical parameters. By comparing pre and post burn-in data, any deviation in the laser performance can be evaluated and infant mortality failures are eliminated. High burn-in yield is proof of the excellent reliability of the devices.

## VIII. Results

### A. Geometrical Results

The stringent requirements on repeatability and accuracy of the epoxy printing, as well as the diode pick&place precision were met.

The die placement accuracy can be  $\pm 10\mu\text{m}@3\sigma$ , the die rotation  $<5^\circ$ .

The employed HA3 gold bonding wire [9] delivers a better loop stability and higher loop reproducibility than doped 4N gold bonding wires like HD2 with high ductility [10].

The perfected wire bond process secured a homogeneous monometallic structure of the wire bonds and reduced, well defined bond loop heights, with sufficient clearance of the bonding wire above the VCSEL surface.

### B. Results of the Mechanical Measurements

Careful optimization of the wire bond process has been necessary. The results are proof of the excellent quality of the wire bonds and the process capability.

The wire bond parameters have been engineered to meet the shear test limits specified in [7] and [8].

### C. Electro-Optical Results

The electro-optical VCSEL performance is characterized over laser current and optical output power. The data presented in this section shows that the laser array performance is not affected by the assembly process steps.

Table I shows the obtained optical output power of 2D VCSEL arrays manufactured by VERTILAS.

Table I: Optical output power  $P_o$  (qcw) of several 2D VCSEL arrays from VERTILAS

# of emitters	$P_o$ (qcw)
12	0.125 W
24	0.25 W
48	0.5 W
160	1.5 W
300	3 W
480	5 W
800	8 W

Fig. 10 shows the optical peak power  $P$  (in qcw mode) and voltage as a function of the drive current of a 2D VCSEL array with 300 emitters, measured with 150  $\mu$ s pulses at a frequency of 50 Hz. An example of the optical output peak power  $P$  (in qcw mode) as a function of the drive current of a 2D VCSEL array with 800 emitters is shown in fig. 11, where the pulse widths is 300  $\mu$ s and the repetition rate is 5 Hz.

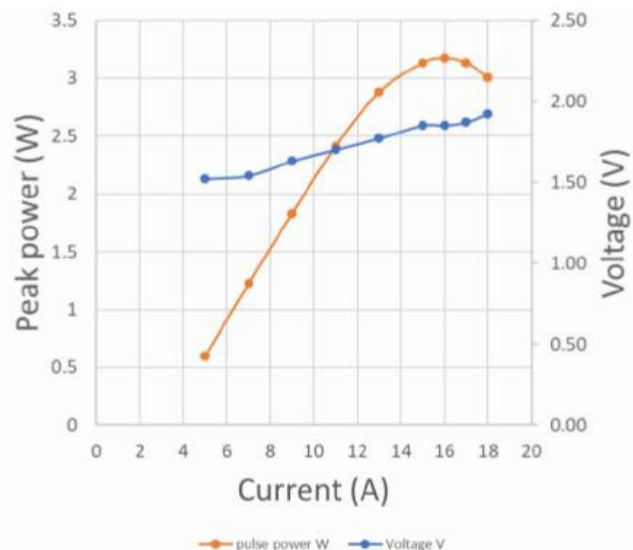


Figure 10: Optical peak power  $P$  (qcw) and voltage as a function of the drive current of a 2D VCSEL array with 300 emitters (150  $\mu$ s pulse, 50 Hz)

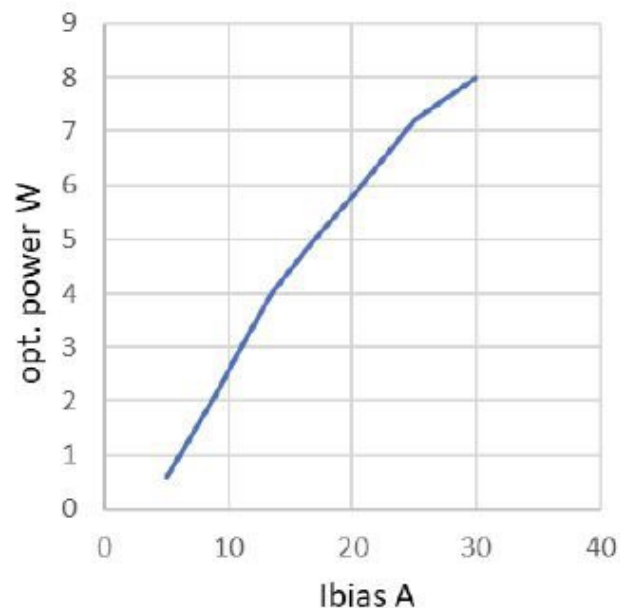


Figure 11: Optical peak power  $P$  (qcw) as a function of the drive current of a 2D VCSEL array with 800 emitters (300  $\mu$ s pulse, 5 Hz)

More results will be presented at the conference.

## IX. Discussion

Careful consideration of the methods and tools as well as proper process development of the die bonding process make it possible to pick and place these thin, fragile III-V 2D arrays and to obtain the required placement accuracy and high yields for cost effective manufacturing of large quantities of 2D VCSEL arrays with wavelengths from 1.3

to 2.3 $\mu\text{m}$ . Bond line thickness control, array coplanarity to the substrate and void free VCSEL array attach, as well as choosing the right die attach material are important factors in ensuring proper thermal transfer. It is obvious that by minimizing the thermal impedance of the packed VCSEL array to keep the junction temperature down significant gains in live time can be achieved. Due to the temperature sensitivity of the VCSEL arrays we ruled out the use of gold-tin soldering processes, well suited for other optoelectronic devices [22]. The perfected wire bond process secured a homogeneous monometallic structure of the wire bonds, a reduced, well defined bond loop height with sufficient clearance of the bonding wires above the VCSEL array surface.

Further iterations and optimizations on the packaging will address cost reduction while still maintaining a manufacturable mind-set.

## X. Applications

One main application of long-wavelengths 2D VCSEL arrays are light detection and ranging (LiDAR) systems, which categorize the objective recognition modes using either structured lighting or the time-of-flight (ToF) detection [24]. Utilizing 1550-nm wavelength with its much higher eye safety lends itself perfectly to this approach. A broad range of other 3D sensing applications is developing. Many publications are known for GaAs based VCSEL arrays with 980nm, 940nm, or shorter wavelength, for instance [23]-[31]. We report solutions with 1.3 to 1.6  $\mu\text{m}$  wavelength for improved eye safety and other advantages, however. Our 2D arrays can be customized to scale up optical output power in order to match customer requirements. Some other important applications include high channel count interconnects for data communication [32], chip-level optical interconnects, free-space optical communication (FSO) in the optical transmission windows of 1310 nm and especially 1550 nm, illumination, and special industrial heating applications.

## XI. Summary

VCSELs can be implemented in a 2D array, enabling a single die to comprise tens, hundreds or even thousands of individual long-wavelength light sources to increase optical output power. In this paper, we report the manufacturing technology for the packaging and some results of InP based 2D VCSEL arrays.

With the optimized screen-printing process described in chapter III we did get a reproducible height of the conductive glue of about 45  $\mu\text{m}$  with low standard deviation, as required. The chosen monometallic contact system increases long-term reliability. Gold wire SSB bonding delivered excellent results, meeting the customer specification, and exceeding

the requirements in [7].

We could demonstrate that an established VCSEL technology [11]-[20] can be adapted with new designs and adapted packaging technologies to new, in many cases disruptive applications. 2D arrays can be supplied by VERTILAS with up to 30 Ampere of current, thus further increasing the need for low tolerance, high precision manufacturing processes. Bond Line Thickness control, VCSEL array coplanarity to the substrate and void free attach, as well as choosing the right attach material are important factors in ensuring proper thermal transfer.

## XII. Outlook

Integration of VCSEL arrays with Silicon Photonics is possible and under investigation.

We consider the use of flip-chip interconnects instead of wire bonds for high-frequency applications.

GaSb VCSELs with a wavelength  $>2.3\mu\text{m}$  are under development.

Future work will be focusing on the thermo-mechanical reliability and will be published later.

## XIII. Conclusion

We developed an assembly technology for long-wavelength ( $\lambda=1.3\text{--}2.3\mu\text{m}$ ) 2D VCSEL arrays. Application-oriented co-development of VCSEL array design and VCSEL array packaging technology for those 2D laser arrays enable new, in some cases disruptive utilizations. Decisions on the design of the package are always related to their effects on other parts of the system. The paper presented the main manufacturing steps and some obtained results.

Due to the very high thermal conductivity of the integrated gold heat spreader and heat sink, the performance of the laser arrays is higher-than-average [21].

The monometallic contact system contributes to the high reliability and long lifetime of the VCSEL arrays.

The result is clear, 2D VCSEL arrays are capable of successfully competing with other products on price with superior performance and reliability.

## Acknowledgment

The authors would like to thank Simon Tätzner for printing the gold-filled epoxy, Bernd Burger for cross sectioning of samples and photomicrographs, and Maximilian Streibl for valuable contributions to this work.

## References

- [1] R. Michalzik (ed.), *VCSELs. Fundamentals, Technology and Applications of Vertical-Cavity Surface-Emitting Lasers*, Springer, 2013, ISBN 978-3-642-24986-0.

- [2] R. Dohle, T. Friedrich, J. Guo, and J. Göbner, "New assembly technology for VCSEL arrays comprising ultra-thin diodes," Presentation at the 22<sup>nd</sup> European Microelectronics and Packaging Conference, Pisa, Italy, September 16-19, 2019.
- [3] R. Dohle; G. Henning; M. Wallrodt; C. Gréus; C. Neumeyr, "Advanced Packaging Technology for Novel 1-dimensional and 2-dimensional VCSEL Arrays," 54<sup>th</sup> International Symposium on Microelectronics, San Diego, CA, October 11-14, 2021, pp. 265-270.
- [4] S. Behler, W. Teng, A. Podpod, "Key Properties for Successful Ultra Thin Die Pickup," Proceedings of the IEEE 67<sup>th</sup> Electronic Components and Technology Conference (ECTC), pp. 95-101, 2017.
- [5] R. C. Garcia, "Improving Stitch Bond on Hybrid Thick Film Substrate using Stand-Off Stitch Wire Bond Technique," 48<sup>th</sup> International Symposium on Microelectronics, October 2015, pp. 425-429.
- [6] H. Xu, A. Shah, B. Milton, and I. Qin, "Wire Bonding Advances for Multi-Chip and System in Package Devices," 51<sup>st</sup> International Symposium on Microelectronics, October 2018, pp. 583-588.
- [7] DVS Verband, "Prüfverfahren für Drahtbondverbindungen," Merkblatt DVS 2811, February 2017.
- [8] JEDEC Standard, "Wire Bond Shear Test Method," JESD22-B116B, April 2017.
- [9] *Heraeus Fact Sheet Au HA3*, Heraeus Materials Technology GmbH & Co. KG, Contact Materials Division, 2022.
- [10] *Heraeus Factsheet Au HD2 4N Gold Bonding Wire for Universal Use*, W. C. Heraeus GmbH & Co. KG, Contact Materials Division, 2022
- [11] M. Verplaetse, L. Breyne, C. Neumeyr, T. De Keulenaer, W. Soenen, X. Yin, P. Ossieur, G. Torfs, and J. Bauwelinck: "DSP-free and real-time transmission of 50Gb/s NRZ over 15km SSMF and 64Gb/s NRZ B2B with a 1.3 $\mu$ m VCSEL," Optical Fiber Communications Conference and Exposition (OFC), San Diego, CA, 2018.
- [12] A. Malacarne, C. Neumeyr, W. Soenen, F. Falconi, C. Porzi, T. Aalto, J. Rosskopf, J. Bauwelinck, and A. Bogoni: "Optical transmitter based on a 1.3 $\mu$ m VCSEL and a SiGe driver circuit for short-reach applications and beyond," IEEE Journal of Lightwave Technology, 2018.
- [13] A. Gatto, P. Parolari, C. Neumeyr, and P. Boffi, "Beyond 25 Gb/s Directly-Modulated Widely Tunable VCSEL for Next Generation Access Network," Optical Fiber Communications Conference and Exposition (OFC), San Diego, California, 2018, paper Th1E.2., doi.org/10.1364/OFC.2018.Th1E.2.
- [14] A. Gatto, P. Parolari, M. Rapisarda, P. Martelli, C. Neumeyr, and P. Boffi, "Beyond 50 Gb/s Directly-Modulated Long-Wavelength VCSELS for Next-Gen Access Network (Invited)," IEEE Summer Topical Meetings, Ft. Lauderdale, Florida, USA, July 2019, paper MB4.1., doi.org/10.1109/PHOSST.2019.8795016.
- [15] Gatto, G. Delrosso, G. Parladori, P. Parolari, S. Bhat, C. Neumeyr, M. Svaluto Moreolo, and P. Boffi, „Long wavelength InP VCSEL exploitation for innovative sustainable high-capacity transmitter," 20<sup>th</sup> VDE ITG Photonic Networks Conference, 2021.
- [16] N. Eiselt, H. Griesser, J. Wei, R. Hohenleitner, A. Dochhan, M. Ortsiefer, M. Eiselt, C. Neumeyr, J. J. Vegas Olmos, I. Tafur Monroy: "Experimental Demonstration of 84 Gb/s PAM-4 over up to 1.6 km SSMF Using an 20-GHz VCSEL at 1525 nm," IEEE Journal of Lightwave technology, February 2017.
- [17] M. Verplaetse, L. Breyne, C. Neumeyr, T. De Keulenaer, W. Soenen, X. Yin, P. Ossieur, G. Torfs, and J. Bauwelinck: "DSP-free and real-time transmission of 50Gb/s NRZ over 15km SSMF and 64Gb/s NRZ B2B with a 1.3 $\mu$ m VCSEL," Optical Fiber Communications Conference, 2018.
- [18] T. Aalto, M. Harjanne, T. Vehmas, M. Karppinen, A. Sitomaniemi, A. Malacarne, C. Neumeyr, and J. Bauwelinck: "Transceivers for 400G based on hybrid integrated thick SOI and III/V chips," 43<sup>rd</sup> European Conference on Optical Communication (ECOC 2017), Gothenburg, Sweden, September 17, 2017-21, 2017.
- [19] M. Svaluto-Moreolo, L. Nadal, J. M. Fàbrega, F. J. Vilchez, C. Neumeyr, A. Gatto, P. Parolari, and P. Boffi, "VCSEL-based sliceable bandwidth/bitrate variable transceivers," Proceedings SPIE 10946, Metro and Data Center Optical Networks and Short-Reach Links II, 1094606, February 1, 2019, doi: 10.1117/12.2509316.
- [20] M. Ortsiefer, W. Hofmann, J. Rosskopf, and M.-C. Amann: "Long-Wavelength VCSELS with Buried Tunnel Junction", Chapter 10 in *VCSELS - Fundamentals, Technology and Applications of Vertical-Cavity Surface-Emitting Lasers*, Springer Series in Optical Sciences, Vol. 166, ISBN 978-3-642-24985-3.
- [21] R. Dohle, G. Henning, T. Friedrich, M. Wallrodt, C. Gréus, C. Neumeyr, J. Rosskopf, R. Hohenleitner, "New Packaging Technology for Disruptive 1- and 2-Dimensional VCSEL Arrays and Their Electro-Optical Performance and Applications," 72<sup>th</sup> Electronic Components and Technology Conference (ECTC), San Diego, California, May 31 - June 3, 2022.
- [22] R. Dohle, J.J. Callahan, T.J. Drabik, K.P. Martin, "A new cost-effective packaging technique for optoelectronic devices," 46<sup>th</sup> Electronic Components and Technology Conference (ECTC), Orlando, Florida, May 28 - 31, 1996.
- [23] M.E. Warren, D. Podva, P. Dacha, M. K. Block, C. J. Helms, J. Maynard, R. F. Carson, "Low-divergence high-power VCSEL arrays for lidar application," Proc. SPIE 10552, Vertical-Cavity Surface-Emitting Lasers XXII, February 19, 2018.
- [24] H. Kalagara, G. Zhao, J. Yang, B. Kesler, M. A. Shirazi, M. Mansourea, Q. Yu, M. Peters, "Very compact multi-junction VCSEL arrays," Proc. SPIE 1212020, Vertical-Cavity Surface-Emitting Lasers XXVI, March 28, 2022.
- [25] K.-B. Hong, W.-T. Huang, H.-C. Chung, G.-H. Chang, D. Yang, Z.-K. Lu, S.-L. Chen, H.-C. Kuo, "High-Speed and High-Power 940 nm Flip-Chip VCSEL Array for LiDAR Application," Crystals 2021, 11, 1237.
- [26] N. Haghghi, J.A. Lott, "Electrically Parallel Three-Element 980nm VCSEL Arrays with Ternary and Binary Bottom DBR Mirror Layers," Materials 2021, 14, 397.
- [27] Z. Khan, J.-C. Shih, R.-L. Chao, T.-L. Tsai, H.-C. Wang, G.-W. Fan, Y.-C. Lin, J.-W. Shi, "High-brightness and high-speed vertical-cavity surface-emitting laser arrays," Optica Vol.7, No. 4, April 2020.
- [28] W.-C. Lo, W.-L. Wu, C.-H.-Cheng, C.-T.- Tsai, H.-C. Kuo, G.-R. Lin, „Regional Pulsewidth and Nonuniformity of Modulated 940 nm Vertical-Cavity Surface-Emitting Laser Array," Adv. Photonics Res. 2022, 3, 2100133.
- [29] S. Liverman, H. Bialek, A. Natarajan, A.X. Wang, "VCSEL Array-Based Gigabit Free-Space Optical Femtocell Communication," Journal of Lightwave Technology Vol. 38, Issue 7, pp. 1659-1667 (2020).
- [30] N. Haghghi, P. Moser, M. Zorn, J.A. Lott, "19-Element 2D Top-Emitting VCSEL Arrays," Journal of Lightwave Technology Vol. 39, Issue 1, pp. 186-192 (2021).
- [31] C. Wang, C. Li, Z. Wang, "Analysis of optical and thermal properties of 940-nm vertical-cavity surface-emitting lasers," Springer Optical and Quantum Electronics 54 (7), July 2022.
- [32] H. Chen, C. Li, N. K. Fontaine, B. Farah, C. Bolle, R. Ryf, M. Mazur, L. Dallachiesa, D. T. Neilson, O. Raz, R. Hohenleitner, C. Neumeyr, "10-Mode-Multiplexed Transmitter Employing 2-D VCSEL Matrix," 2021 European Conference on Optical Communication (ECOC), Bordeaux, France, September 13-16, 2021