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Major Goals: The primary objective of this proposal is to create the wafer bonding capability at Clemson University to support several ongoing photonic integration related projects supported by the DoD. This new capability will also enable many other research projects in photonics and electronics and greatly enhance research-orientated education of undergraduate and graduate students.

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Training Opportunities: Please see the attached report.

Results Dissemination: Nothing to Report

Honors and Awards: Nothing to Report

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Final report: Wafer bonding for hybrid photonic integration research

1. Introduction and Overview

The primary objective of this proposal is to create the wafer bonding capability at Clemson University to support several ongoing photonic integration related projects supported by the DoD. This new capability will also enable many other research projects in photonics and electronics and greatly enhance research-orientated education of undergraduate and graduate students. The requested funds will be used to purchase an EVG 500 series wafer bonder. The EVG 500 series wafer bonder is an advanced wafer bonding tool that supports multiple wafer bonding techniques and substrate materials. EVG's wafer bonders are known to achieve the highest yields for aligned wafer bonding and have set industry standards. Contributing to the success of EVG's wafer bonders, the innovative bond chamber design, precision wafer fixtures and the process separation principle are major criteria for precise and uniform bonds. The wafer bonding systems are based on a modular chamber design that ensures an easy process migration from R&D to production. With the highest number of bonder installations in the field, EVG is the industry leader with field-proven technology and most extensive experience in manufacturing wafer bonding equipment.

Major advances have recently been made at Clemson University in developing and employing advanced optical and electrical materials for applications ranging from fundamental science to applied engineering research. Researchers have been able to model the physics behind these materials and employ these models to modify their optical, electrical, and mechanical properties. Clemson also has significant characterization and measurement resources, including a state-of-the-art electron microscope facility, a cleanroom facility for micro and nanofabrication, an optoelectronic characterization facility that is set up by using the start-up funds of several Clemson's new faculty members. The time is prefect to exploit these efforts and advances by creating integrated and multifunctional photonic and electronic devices and systems. Photonic hybrid integration related research has become a central part of this new initiative. This proposal seeks to acquire the wafer bonding equipment to enhance such cross-cutting collaborative efforts (Prof. Lin Zhu, Prof. Liang Dong, Prof. Eric Johnson, and Prof. John Ballato). Programs in some new research areas will also be enabled by the requested equipment, including microfluidics, plasmonics, and biophotonics. Equally important is education. If funded, this project will also provide many interdisciplinary opportunities to educate and train undergraduate and graduate students in integrated photonics and micro/nanofabrication. In particular, students will be able to both *fabricate and characterize* novel micro/nanoscale optoelectronic devices at Clemson and gain hands-on research experiences.

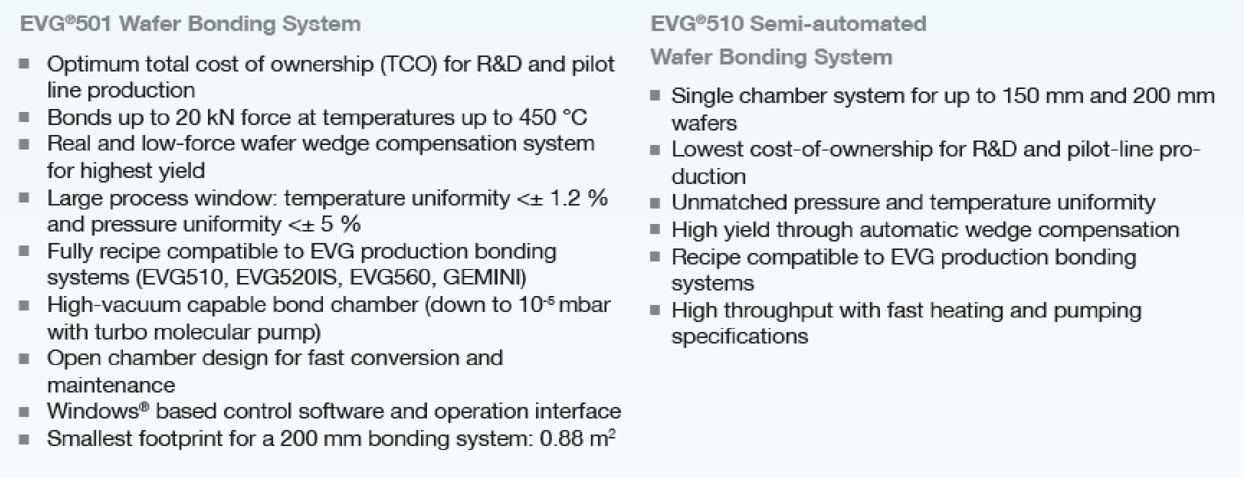
Photonic integrated circuit is a device that integrates multiple photonic functions, such as light generation, detection, modulation, filtering, routing and nonlinear processing, on a small chip [1-6]. Similar to its electronic counterpart - electronic integrated circuit, photonic integrated circuit can significantly reduce the system size, weight, operation power, and cost and it has many important applications in sensing, signal processing, and communication. During the last few years, optical interconnects in data centers and optical access networks at the individual user level have become more and more popular in order to meet the increasing demand for bandwidth and speed. It is not hard to imagine that future personal computers, home entertainment systems, and even mobile devices such as cellphones should be able to directly access high speed optical network. However, current optical chip technology cannot efficiently provide necessary functionalities such as signal regeneration and buffering, coherent wavelength conversion, and packet routing/scheduling to enable this possibility. In other words, we will need more powerful and complex multifunctional photonic integrated circuits to realize the next breakthrough.

Unlike the electronics industry where silicon is the dominant material platform for integration, various photonic integrated circuits, such as optical transceivers, tunable lasers, optical modulators, and wavelength selective detectors, have been fabricated in different material systems based on different integration technologies. This is mainly because different material platforms in photonics offer certain advantages and limitations at the same time and thus ***there is no "the one" material platform for integrated photonics***. Commercially available photonic integrated circuits are generally fabricated in III-V semiconductor (GaAs and InP) and silicon based material platforms [7-10]. III-V semiconductors are good for light generation and detection, but the integration of both active and passive devices requires complex epitaxy regrowth. Although III-V materials have excellent nonlinear properties (both second order and third order), the relatively large waveguide size and challenge to satisfy the phase matching condition prevent these materials from being widely used for chip-scale integrated nonlinear optics. Silicon based platform has desirable properties for passive components (silicon oxide and nitride) and modulators (silicon), but it is very difficult to realize electrically-driven laser sources because of the indirect bandgap material property. Silicon on insulator (SOI) waveguides can provide tight optical confinement and large third order optical nonlinearity, but two-photon absorption limits the maximum light intensity. Thus SOI waveguides are not suitable for nonlinear processes that require high power CW light input, such as micro-resonator based frequency comb generation.

In recent years, hybrid integration of active and passive components in different material systems has attracted intense interests in order to create next generation multifunctional photonic integrated circuits [11-30]. The main motivation is to ***realize each desired photonic function by using the best suitable material and create the whole system based on hybrid integration.*** In one hybrid integration approach, active and passive components are separately fabricated on different sub-chips and then are integrated/bonded on a pre-patterned motherboard chip by use of the end-to-end coupling through mode converters on each sub-chip [11-19]. Another approach directly integrates III-V gain chips on silicon through direct wafer bonding to create electrically pumped lasers and amplifiers for silicon based components [20-30]. Wafer bonding is a technology to join two substrate materials with different structural properties. Depending on the chemistry that bonds different substrate materials, wafer bonding can be classified into different categories, such as direct bonding, surface activated bonding, anodic bonding, eutectic bonding, and adhesive bonding. It is clear that the combination of different material systems through wafer bonding can overcome the limitation of a conventional single material system, such as silicon or IIIV semiconductors. Thus, exploring new material platforms through wafer bonding for hybrid photonic integration has become a driving force to realize novel complex and multifunctional photonic devices. Through the DURIP program, the requested equipment will enable the wafer bonding capability for photonic hybrid integration research at Clemson.

2. Detailed descriptions of the purchased equipment

With over 15 years experience in designing and manufacturing precision wafer bonding equipment, **EVG wafer bonding systems** are well recognized in setting industry standards for the MEMS production industry. Besides supporting wafer level and advanced packaging, 3D interconnects and MEMS fabrication, the EVG 500 series wafer bonding systems can be configured for R&D, pilot-line or volume production. They accommodate the most demanding applications by bonding under high vacuum, precisely controlled fine vacuum, temperature or high pressure conditions. Multiple bonding methods including anodic, thermo compression, glass-frit, epoxy, UV and fusion bonding are covered. Based on a unique modular bond chamber design the EVG500 series allow for an easy technology transfer from R&D to high volume production.



EVG®501 Wafer Bonding System

- Optimum total cost of ownership (TCO) for R&D and pilot line production
- Bonds up to 20 kN force at temperatures up to 450 °C
- Real and low-force wafer wedge compensation system for highest yield
- Large process window: temperature uniformity <± 1.2 % and pressure uniformity <± 5 %
- Fully recipe compatible to EVG production bonding systems (EVG510, EVG520IS, EVG560, GEMINI)
- High-vacuum capable bond chamber (down to 10^{-5} mbar with turbo molecular pump)
- Open chamber design for fast conversion and maintenance
- Windows® based control software and operation interface
- Smallest footprint for a 200 mm bonding system: 0.88 m^2

EVG®510 Semi-automated Wafer Bonding System

- Single chamber system for up to 150 mm and 200 mm wafers
- Lowest cost-of-ownership for R&D and pilot-line production
- Unmatched pressure and temperature uniformity
- High yield through automatic wedge compensation
- Recipe compatible to EVG production bonding systems
- High throughput with fast heating and pumping specifications

Figure 1 The unique features of EVG 500 series wafer bonders


EVG®501
Bond chamber of **EVG®510**

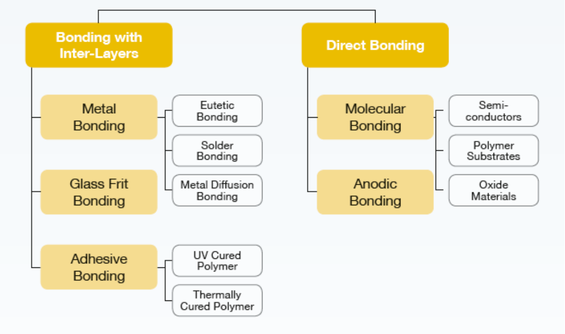


Figure 2 EVG 500 series wafer bonders

The EVG500 bond chamber is equipped with a universal bond cover that allows fast evacuation, rapid heating and cooling. Both anodic and pressure bonding processes are possible within one chamber. Bonding can be performed under vacuum or controlled atmosphere conditions. Independent temperature control of the top and bottom wafer compensates for different thermal expansion coefficients, resulting in stress-free bonding and excellent temperature uniformity. SOI/SDB pre-bonding under vacuum can be performed without hardware reconfiguration. The bond chucks carry the aligned wafer stacks from the aligner to perform the subsequent bonding procedure. Various wafer sizes and bond applications can be handled with a dedicated chuck that fits into each universal bond chamber. The unique features of EVG500 series wafer bonders are shown in Fig. 1. The images of EVG500 series wafer bonders and the supported bonding processes are shown in Fig. 2.

3. Installed equipment

We have completed the installation of the EVG-501S wafer bonder and placed it at the AMRL cleanroom. Figure 1 shows the wafer bonder in the cleanroom. We have tested the heating process for half an hour with a maximum temperature around 550 degree under high vacuum. The next step is to build a reliable recipe to achieve the GaAs on Silica bond. This process includes sample preparation (surface cleaning and activation), sample load, program auto setup (chamber pump down, sample heating with high pressure, chamber cool down). We are expecting to optimize the recipe for the GaAs on Silica bond in the following months.

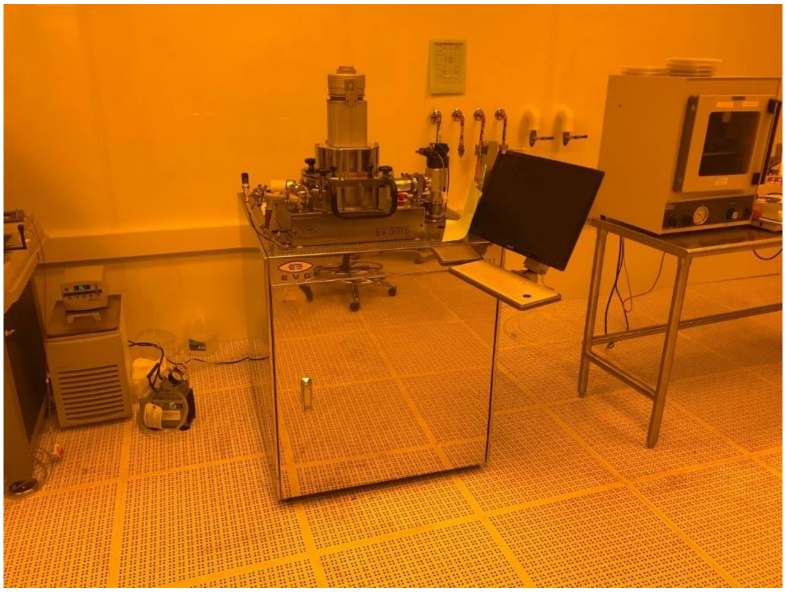


Fig. 3 The wafer bonder in the AMRL cleanroom

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