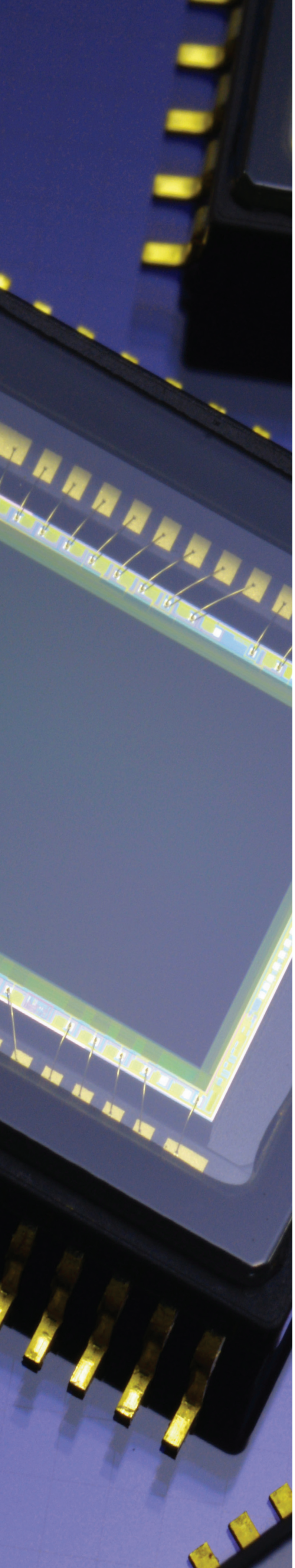

MASTERBOND®
CASE STUDY

EP29LPSPAO-1 Black Adhesive for Construction of Photodiode Arrays for Use at Cryogenic Temperatures

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Adhesive for Construction of Photodiode Arrays for Use at Cryogenic Temperatures

Researchers document the use of Master Bond EP29LPSPAO-1 Black in the construction of optical-fiber-coupled photodiode arrays for use at cryogenic temperatures. Paired with a Josephson junction array (JJA), the photodiode module provides a means to deliver the input signal via laser pulse to the JJA without direct electrical link to the pulse pattern generator. Devices like JJA require cryogenic temperatures to exhibit superconducting properties. During operation, these devices face extreme temperature swings—from 4K to 300K (room temperature)—necessitating careful selection of all materials to minimize thermal stresses. The authors report both empirical and simulation-based results showing the feasibility of constructing fiber-coupled photodiode modules needed for use with Josephson arbitrary waveform synthesizers (JAWS) circuits.

Application

The development of superconducting JJA circuits has had a profound impact on the field of electrical metrology.[1] Applications include precise alternating current (AC) voltage calibration, arbitrary impedance comparison, and AC power measurements. Fundamentally, the SI definition for the volt is defined by the Josephson effect.[2] Initial implementations used microwave frequency to excite the JJA to produce a direct current (DC) voltage. Current research seeks to expand the capabilities of these devices to include the synthesis of AC and arbitrary voltage waveforms using JAWS.

For the device to reach a superconductive state, it must operate at cryogenic temperatures. Engineering a reliable device capable of thermal cycling between ambient temperature and cryogenic temperatures as low as 4K requires careful selection of materials. The circuits include various materials of construction including silicon dies, organic PCB substrates, solder/wiring components, among others. Key material properties include the coefficient of thermal expansion (CTE) as well as temperature-dependent modulus. As the device cools, the materials of construction contract at variable rates allowing stresses to build within the assembly. The die composed of silicon, a brittle material with very low CTE, may catastrophically fracture if the CTE and modulus of the adhesive and PCB substrate is not properly controlled. Thermal management is critical to microelectronic applications with cryogenic environments posing particular challenges due to the reduced compliance faced by materials at exceedingly low temperatures.

Existing JAWS designs utilize a signal generator with a direct electrical link to the JJA necessitating the feed of high-frequency cables into the cryogenic chamber.[2] This thermal load makes it more difficult to cool the chamber as well as leading to electromagnetic interference. To improve on this design, the authors sought to develop an optical-fiber-coupled photodiode array coupled to a JJA capable of receiving pulse transmission via laser from the signal generator. The device itself is composed of an optical fiber secured via ferrule to a precisely aligned sleeve to allow for precise optical coupling with the photodiode. See **Figure 1.** Thermal management of the device is made more complex due to direct bonding of the alignment sleeve to the silicon substrate—the silicon die accumulates thermal stress both from the bonded alignment sleeve as well as from the bottom connection with the PCB. The photodiode was flip-chip bonded to the carrier with epoxy underfill for enhanced thermal-mechanical robustness.

Key Parameters and Requirements

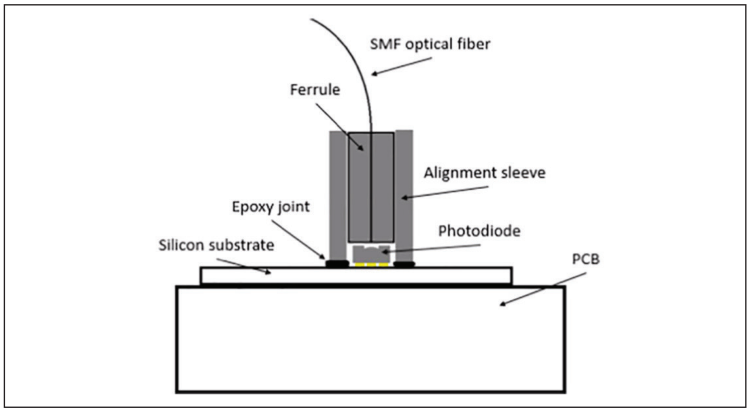

Figure 1. Schematic of optical-fiber-coupled photodiode array. Device includes alignment sleeve bonded to silicon substrate via epoxy enabling precise optical alignment between optical fiber and photodiode. Photodiode is flip-chip bonded with epoxy underfill.[3]

Generally, desirable properties for an epoxy adhesive in microelectronic applications include high thermal conductivity, high electrical resistivity, a low CTE, and low modulus. For this cryogenic application, the assembly must have a high degree of mechanical and thermal robustness over the wide temperature range of 4K to 300K. To prevent die cracking, the epoxy must maintain a high degree of compliance and possess minimal contracture when transiting between the two temperatures.[3] It should also be noted that the assembly in question requires three different applications of epoxy during construction: 1) capillary flow underfill for the flip-chip bonding, 2) adhesive bonding the silicon die to the PCB substrate, and 3) adhesive bonding of the alignment sleeve to the silicon die. As underfill bonding and die-to-PCB bonding are fairly routine processes, discussion will primarily address the third application of bonding the alignment sleeve to the silicon substrate. Epoxies used for underfill will have different viscosity requirements when compared with applications such as bonding the alignment sleeve. A low viscosity is ideal for underfill, whereas as a higher viscosity material will be better for fixturing the alignment sleeve prior to cure.

In order to optimize device construction for resistance to cryogenic damage, the authors conducted modelling simulations examining stresses induced upon the die from the alignment sleeve. This included the use of temperature dependent CTE and temperature dependent modulus of the components involved in the joints. The added stresses resulting from the alignment sleeve can be readily visualized in **Figure 2**, this necessitates careful selection of both the bonding epoxy as well as material selection for the alignment sleeve. The authors evaluated both zirconia (CTE: 8.7 ppm/K @ 293K) and borosilicate glass alignment sleeves (CTE: 3.25 ppm/K @ 293K). The CTE of silicon at 293K is 2.6 ppm/K; it would then be expected that borosilicate would result in less thermal stress as it is more closely matched to the silicon.

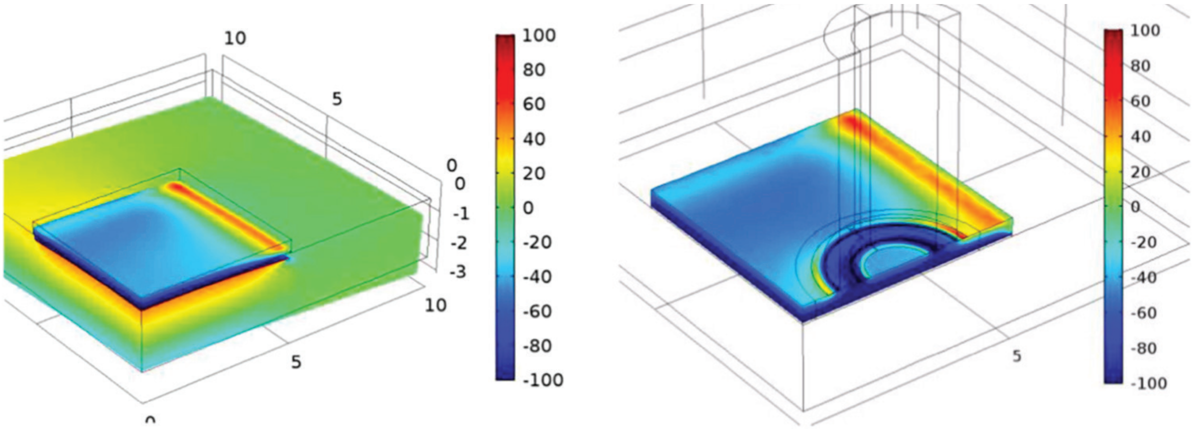

Figure 2. Simulated axial stresses (σxx) at 4K for bare die (left) and silicon die on PCB substrate with zirconia alignment sleeve (right).[3]

Additionally, the authors evaluated different sleeve-substrate gap thicknesses and two different epoxies: Master Bond EP29LPSPAO-1 Black and Stycast 1266. Adhesive properties needed to reduce the risk of thermal cracking are low thermal expansion and a relatively low modulus at the cryogenic temperatures. As the temperature is dropped from ambient to 4K, the adhesives contract and their stiffness/modulus increases. Greater contracture relative to the silicon concentrates stresses, and the increase in modulus minimizes the ability of the adhesive to comply leading to the possibility of die fracture. To determine the CTE and elastic modulus of the adhesives, the authors employed dynamic mechanical thermal analysis (DMTA) and dilatometry. The modulus represented as storage modulus for Master Bond EP29LPSPAO-1 Black from room temperature to -150°C is shown in **Figure 3**. **Figure 4** shows the thermal expansion, $\Delta L/L_0$, over the temperature range of 4-300K of the materials used in construction. From this data, it can be seen that Master Bond EP29LPSPAO-1 Black exhibits significantly less thermal contracture upon cooling to 4K than the Stycast 1266 adhesive. Further, The Young's Modulus of the Master Bond (9 GPa) product was lower (more compliant) than the Stycast product (11 GPa) at 4K. Lower thermal expansion and lower modulus at 4K would be expected to result in reduced risk of thermal cracking during operation.

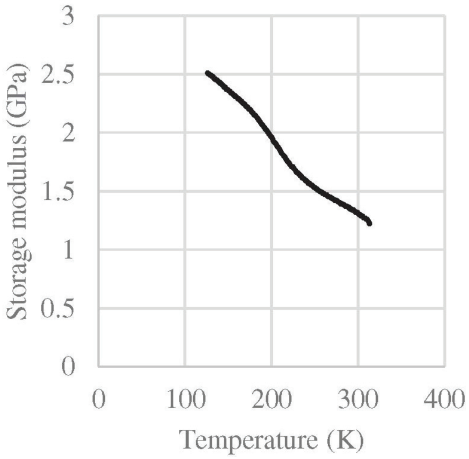

Figure 3. Measured storage modulus for Master Bond EP29LPSPAO-1 Black from room temperature to -150°C.[3]

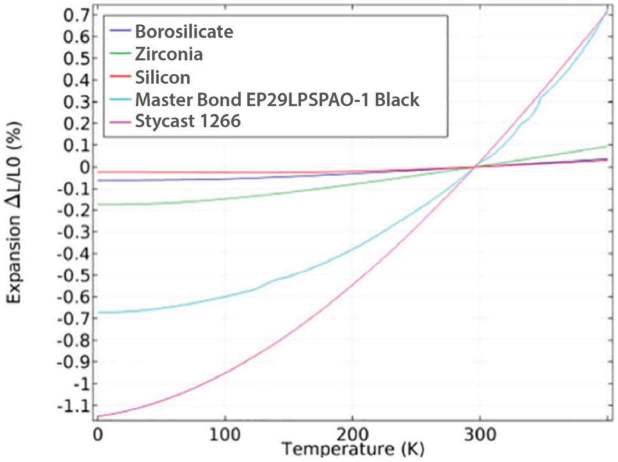

Figure 4. Total thermal expansion relative to room temperature (300K). $\Delta L/L_0$: Master Bond: ~ -0.67%, Stycast: ~ -1.15%.[3]

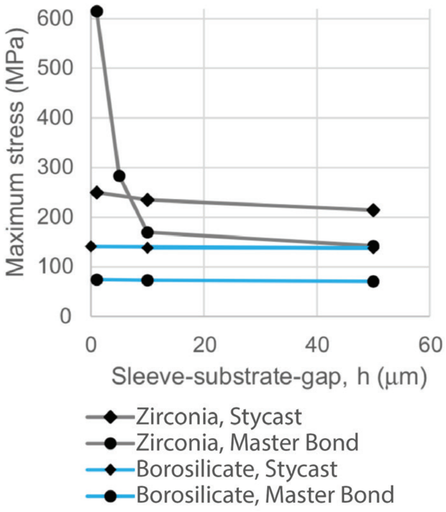

Figure 5. Maximum axial stress in the silicon die at 4K versus the sleeve-substrate distance.[3]

Results

Stress simulations analyses were conducted with zirconia and borosilicate glass alignment sleeves bonded with both Master Bond EP29LPSPAO-1 Black and Stycast 1266 over a range of sleeve-substrate gap thicknesses.[3] Plotted in **Figure 5** is the maximum axial stress experienced by the silicon die. From this analysis, borosilicate offers superior stress protection compared with zirconia due to its reduced thermal expansion. Further, the analyses conducted with Master Bond show an insensitivity to sleeve-substrate gap thickness for the borosilicate glass sleeve when compared with Stycast 1266. Assemblies using Master Bond result in lower maximum stress for all configurations using the borosilicate glass sleeve suggesting greater resistance to thermal cracking. Empirical testing of the devices with thermal cycling between 300K and 77K in liquid nitrogen showed that the devices could handle the thermal shocks while also being capable of handling long-term immersion in liquid Helium. The photodiodes showed no sign of degradation as monitored by dark current; the adhesives showed no failure, and no sign of die cracking or photodiode detachment was observed. The authors conclude that with careful selection of the PCB, alignment sleeve material, and using an epoxy with low CTE and low modulus, a device with reduced tendency to crack in cryogenic environments can be realized.

References

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[2] Bardalen, E., Karlsen, B., Malmbekk, H., et al. *Packaging and demonstration of optical-fiber-coupled photodiode array for operation at 4K.* IEEE Transactions on Components, Packaging, and Manufacturing Technology. 2156-3950. 2017.

[3] Bardalen, E., Karlsen, B., Malmbekk, H., et al. *Reliability study of fiber-coupled photodiode modules for operation at 4K.* Microelectronic Reliability. 81, 362-367. 2018.