Evaluation of Low-Pressure-Sintered Multi-Layer Substrates for Medium-Voltage SiC Power Modules

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Evaluation of Low-Pressure-Sintered Multi-Layer Substrates for Medium-Voltage SiC Power Modules

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Abstract — **Direct-bonded aluminum (DBA) multi-layer substrates have been fabricated using low-pressure silver sintering. These multi-layer substrates can be used to reduce the peak electric field strength inside power modules. This benefit is particularly important for medium-voltage silicon carbide (SiC) MOSFETs due to their higher operating voltages. The voiding content and defect density of the bond used to create the multi-layer substrate stack-up is critical to the thermal performance and reliability of the power module. This work evaluated two low-pressure-assisted sintering techniques; one using nano-silver preform and the other using nano-silver paste to bond 23 mm by 49 mm DBA substrates. C-mode Scanning Acoustic Microscopy (C-SAM) was used to evaluate the bond quality after sintering. To evaluate the reliability of the sintered multi-layer substrates, passive thermal cycling from –40 °C to 200 °C was performed. Cross-sections were cut at pre-determined intervals and imaged with Scanning Electron Microscopy (SEM). After 1,000 thermal cycles, minor cracking was observed, but no failures have occurred.**

Keywords – power module, preform, silicon carbide, reliability, silver sintering, stacked substrates.

I. INTRODUCTION

Medium-voltage (MV) SiC power semiconductor devices have the potential to drastically increase the power density of high-power systems. However, current packaging technologies must be improved to harness the advantages of these SiC devices. In particular, conventional, metal-ceramic substrate technologies are a limiting factor for MV SiC power modules because increasing the ceramic thickness provides diminishing improvements in the partial discharge inception voltage (PDIV), yet causes significant increases in thermal resistance [2]. Multi-layer substrates have been shown to improve this tradeoff by grading the electric field at the triple points [2]. Multi-layer ceramic substrates are not widely available. Different techniques have been employed to fabricate multi-layer substrates with varying degrees of reliability. In [3], it was shown that multi-layer aluminum nitride (AlN) direct bonded copper (DBC) substrates bonded using a SnAgCu solder experienced significant delamination and cracking in the ceramic and bond line after only 124 thermal cycles from –55 °C to 195 °C. Other significant issues are observed in a different design utilizing a AgCuTi brazed metal joint [4]. Metal brazed joints quickly degraded during thermal cycling causing increases in thermal resistance.

Recent research has investigated the feasibility of large-area sintered substrates to create these multi-layer structures [4]–[6]. However, the quality of the sintered bond line using these techniques had wide variability. Achieving a high-quality bond is important to reduce the thermal resistance of the power module. A technique utilizing a nano-silver preform on a polyimide carrier film has been investigated in [7] as a more repeatable method of silver sintering. Sintered silver die attach using a nano-silver preform has been shown to have greater thermomechanical reliability than DBC substrates when exposed to 1000 thermal shocks from –55°C to 125°C [8]. While these results are encouraging regarding the reliability of sintered silver preform, there is little data on larger bonding areas. The silver preform work in [7] and [8] does not analyze any bonding areas larger than 5mm by 5mm.

This work aims to improve the reliability of the multi-layer substrate structure by using AlN DBAs instead of DBCs and silver sintering instead of soldering. DBC substrates fail by ceramic cracking and trace delamination when fatigued through thermal cycling while DBAs do not exhibit these severe failure modes [3] due to closer alignment of the coefficient of thermal expansion between the AlN ceramic and aluminum metallization layers. During thermal cycling, DBA substrates do not delaminate or crack, but the metal surface experiences surface roughening [9], [10]. Sintered silver bonds have also demonstrated improved reliability in large-area bonds compared to the current state-of-the-art, which utilizes solder [5], [9], [11].

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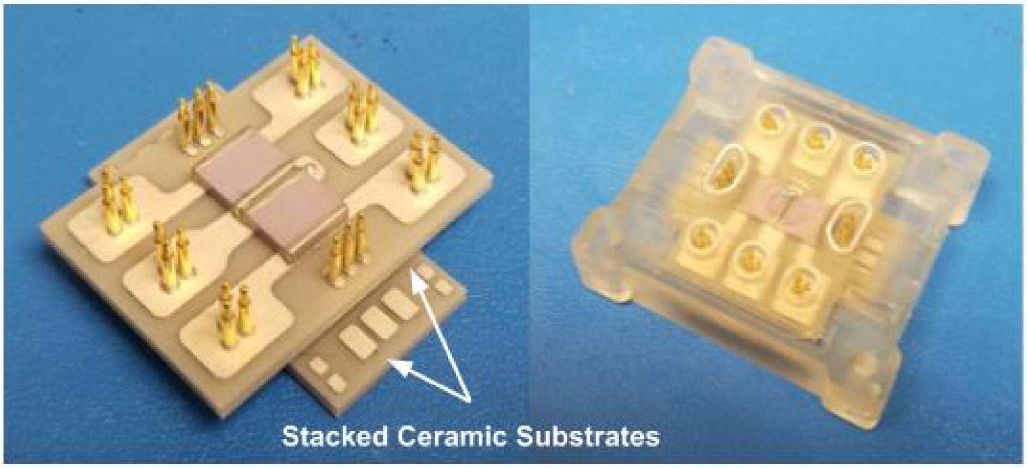


Fig. 1: 10-kV SiC module implementing multi-layer substrates for reduced peak electric field.

Some investigation has been performed on single DBA substrates [10] and comparisons have been made with other substrate materials and fabrication types [12]. However, little information exists on the reliability of large-area bonds. Sintered silver, in particular, has been investigated for feasibility and initial thermal performance, but not long-term thermo-mechanical reliability. Fig. 1 features a 10 kV SiC module design with large-area bonded, multi-layer substrates in its design. Samples of the multi-layer substrates on the bottom of the module in Fig. 1 are evaluated in this investigation.

This work presents the evaluation of two large-area silver sintering methods: 1) screen-printed, open-face contact dried nano-silver paste, and 2) a two-step, large-area silver sintering method utilizing stamp-transferred nano-silver preform. The bond quality is assessed using C-SAM and cross-sections are cut and imaged to evaluate the silver–aluminum interfaces, and identify any areas with crack formation or delamination. To assess the reliability of the resulting large-area-sintered multi-layer DBA substrates, thermal cycling from –40 °C to 200 °C is performed.

II. SILVER SINTERING PROCESSES

Method 1: Nano-Silver Paste

The nano-silver paste was used to bond silver-plated DBAs that are 49.2 mm by 23.1 mm. Each DBA has 1-mm-thick AlN ceramic, and 0.3-mm-thick aluminum metallization layers. A 100-µm layer of nano-silver paste is printed onto each DBA before drying at 125 °C for 30 minutes. The paste is dried using open-faced contact drying [13] to remove most of the organic binder so that voiding caused by its evaporation during sintering can be reduced [13], [14]. Fig. 2 shows the substrates drying on a hot plate with the nano-silver paste printed over the silver-plated aluminum metallization. Once the paste has dried, the two substrates are aligned together. The substrates are then sintered in a Carver bench-top auto press. The platens of the hot press are set to 200 °C at the top and 250 °C at the bottom to achieve a target temperature of 250 °C at the sintered silver bond. Experiments using a thermocouple between two DBA samples confirm that the temperature reached 250 °C given this configuration. 1 MPa pressure is applied during sintering.

Method 2: Nano-Silver Preform

First, the preform is cut to the size of the DBA substrate. Using a Carver bench-top hot press, nano-silver preform is stamped onto one of the DBA substrates using a pressure of 1 MPa for 60 seconds and a bottom platen temperature of 140 °C (Fig. 3a). A pressure-sensitive paper is placed under the DBA substrate to ensure pressure uniformity during this step. The substrates are then aligned, and sintered. The sintering process for this method is shown in Fig. 3b. The substrates were sintered for 90 seconds under 3MPa pressure. The platens of the hot press are set to 200 °C at the top and 250 °C at the bottom to achieve the same target temperature as the nano-silver paste method: 250 °C at the sintered silver bond. Experiments using the thermocouple between two DBA samples were repeated, and again confirmed that the temperature reached 250 °C given this configuration.

III. EXPERIMENTAL RESULTS

Fig. 2: DBA substrates with screen-printed nano-silver paste during open-faced contact drying on a hot plate. Substrates are 49.2 mm in length by 23.1 mm in width.

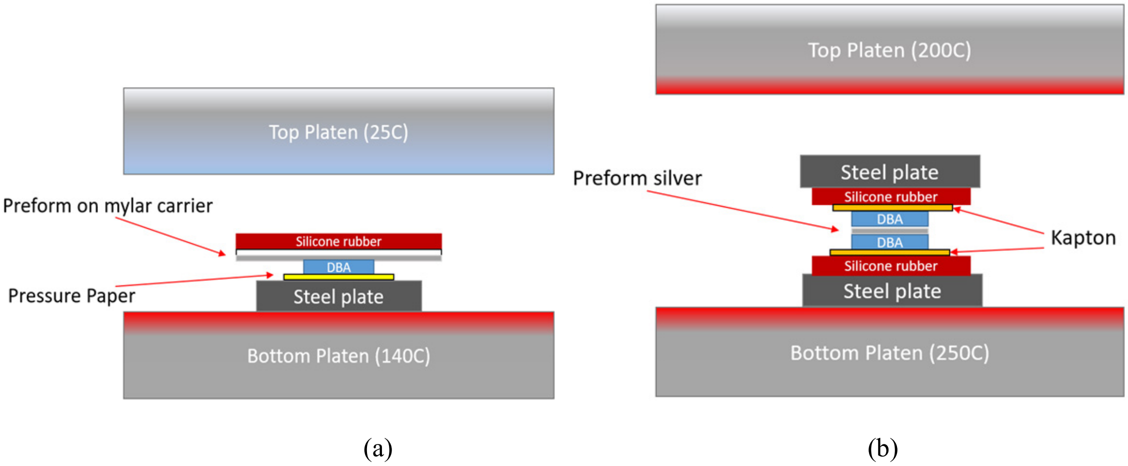


Fig. 3: Diagram of the (a) nano-silver preform stamping process, and (b) sintering procedure.

Thermal cycling tests are an effective method of evaluating the thermomechanical reliability of power modules. Cyclic heating and cooling of power modules causes mechanical stress that fatigues joints over time. Fatigue, and eventually failure, of power modules can be observed by subjecting controlled samples to repetitive heating and cooling. A survey of other thermal cycling tests in literature suggested a cycling profile of –40 °C to 200 °C is appropriate for the multi-layer substrates in this investigation.

15 multi-layer substrates were fabricated for reliability testing, and one stack from each method was fabricated as a reference to analyze the bonding layer without thermomechanical stress. Samples were fabricated with either 1 MPa or 3 MPa sintering pressure. The samples fabricated with the nano-silver preform and 3 MPa sintering pressure were the most uniform of the population when imaged using C-SAM before thermal cycling.

However, C-SAM images of substrate stacks were inconsistent when analyzing samples after thermal cycling began. All bonded substrates in this population have been thermally cycled from –40 °C to 200 °C at NREL. Thermal cycling is critical in determining the resilience of the substrate stack to thermal stress and fatigue. C-SAM images were taken periodically during thermal cycling to track defects or bond failure of the fabricated multi-layer substrates. One sample was selected to image every 50 cycles, and all other samples were imaged every 100 cycles. C-SAM images were difficult to interpret, as each scan of a sample produced a slightly different image of the bond. Re-scanning the same sample would capture some obvious and recognizable features, but the contrast of the image would change with each re-scan, making it difficult to identify any voids or cracks using these images alone. It is likely that the roughening of the aluminum surface of the DBA is the cause of this inconsistency in C-SAM imaging. As thermal cycling progresses, the roughed aluminum is no longer a planar, tangential surface to the ultrasonic transducer and signals are scattered. The thickness variation in the aluminum also causes a fluctuation in the time that an acoustic pulse takes as it travels from the transducer, through the sample, and back, making it difficult to produce a clear image of the sintered silver bond.

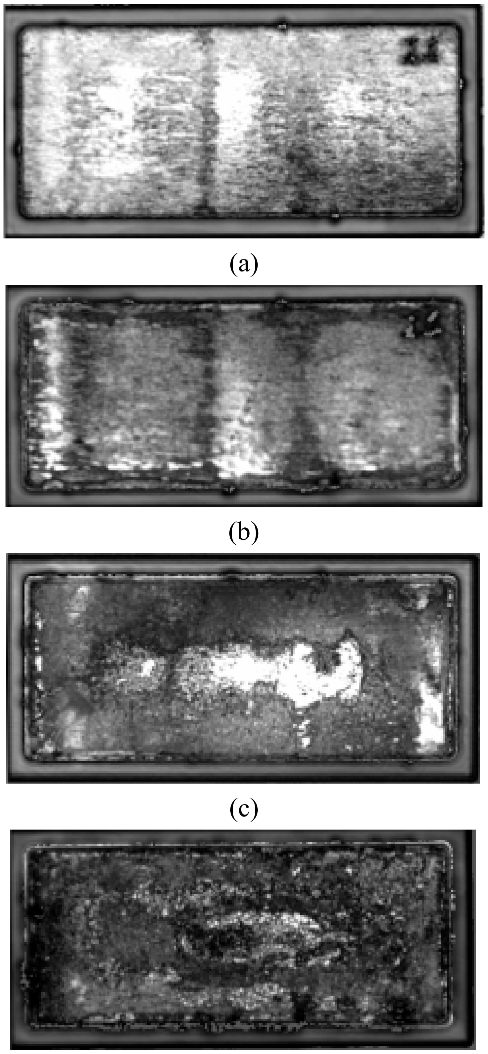
Fig. 4 shows the changes observed during thermal cycling. Fig. 4a and Fig. 4b are CSAM images of a nano-silver preform sample before and after 300 thermal cycles –40 °C to 200 °C. Fig. 4c and Fig. 4d are scans of a nano-silver paste sample before and after the same number of cycles. The lighter gray and white regions in Fig. 4 suggest voids or lower density material in the silver bond line. Some of these regions are not visible in C-SAM scans of the sample after 300 thermal cycles. Fig. 4b shows a darkened image with smaller white regions suggesting a denser bond line with less voiding after 300 cycles from –40 °C to 200 °C. Visual inspection of the samples showed no signs of cracking or delamination at this stage in reliability testing.

Cross-sections of samples were cut and imaged after 300, 400, and 500 thermal cycles to correlate brighter, low-density regions of the C-SAM to voids and cracks in the bond layer. Fig. 5 compares cross-sections of DBA substrate stacks bonded with nano-silver preform at these thermal cycling intervals. Cross-sections were cut parallel to the shorter edge of the multi-layer substrate. Images were collected with an optical microscope after polishing with a diamond slurry with an average particle diameter of 20µm. No significant failures were identified in the optical microscope images, although the interface between the aluminum metal and sintered silver increased in roughness.

Similar thermal cycling experiments performed on single DBA substrates resulted in maximum surface roughening of ±10µm after 300 thermal cycles from –55 ˚C to 250 °C [10]. After 300 thermal cycles from –40 °C to 200 °C, the DBA surface in the multi-layer substrate showed surface roughening up to ±15µm.

Surface roughness in this investigation is reported for thermally cycled samples as the change in metal thickness dimension. DBAs have a metal thickness of 300 µm at the onset of thermal cycling. For the cross-section showed in Fig. 5c, surface roughness altered the average metal thickness by 5.26 µm. The largest visible defect in any imaged sample is a void, 80 µm in diameter, visible at the aluminum interface of the sample in Fig. 5b.

Fig. 6 shows optical microscope images of nano-silver paste samples cut at the same thermal cycle intervals as the nano-silver preform cross-sections. Although not immediately obvious from the optical images, surface roughening on nano-silver paste samples is 1.93 to 2.17 times more severe than a nano-silver preform sample subjected to the same number of thermal cycles.



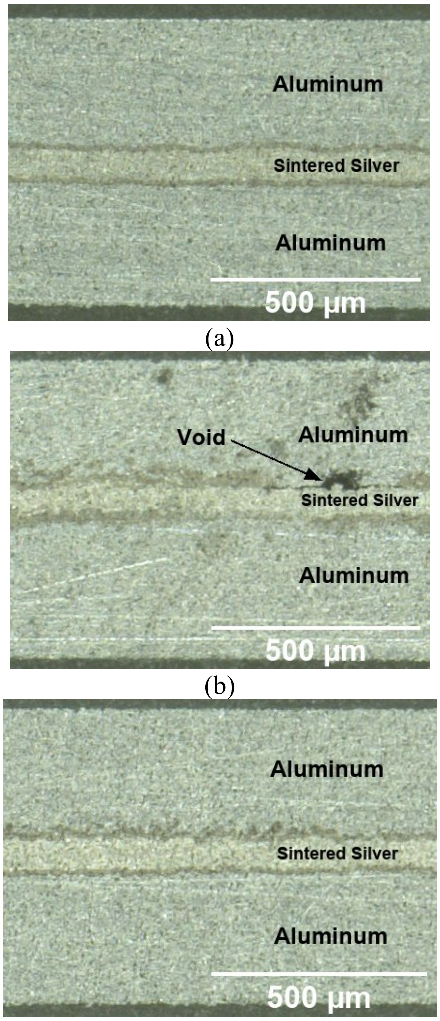
(a)

(b)

(c)

(d)

Fig. 4: C-SAM images of a nano-silver preform sample (a) before and (b) after and nano-silver paste sample (c) before and (d) after 300 cycles from –40 °C to 200 °C.



(a)

(b)

(c)

Fig. 5: Optical microscope images of cross-sections from nano-silver preform samples taken at 300 (a), 400 (b), and 500 (c), thermal cycles from –40 °C to 200 °C.

The average surface roughness is calculated for a 3.3-mm length of the cross-section using an open-source image processing tool. Table 1 summarizes the mean surface roughness for each sample at each thermal cycling milestone. Scanning electron microscope (SEM) images confirmed that the sintered silver bond has not significantly degraded. Fig. 7 is an image of the same sample depicted in Fig. 5c and shows the presence of a small crack in the sintered silver. The length of the crack after 500 thermal cycles is 117 µm. Cracks and voids observed in both optical microscope images as well as the SEM image in Fig. 7 occur at the aluminum-sintered silver interface and propagate parallel to the DBA surface.

Despite minor cracking and changes in surface roughness, the multi-layer substrates show no obvious signs of failure after 500 thermal cycles. The silver bonding layer appears uniform and shows little degradation in the sintered joint.

Although no failures are observed in any samples, the increased surface roughening of the nano-silver paste samples

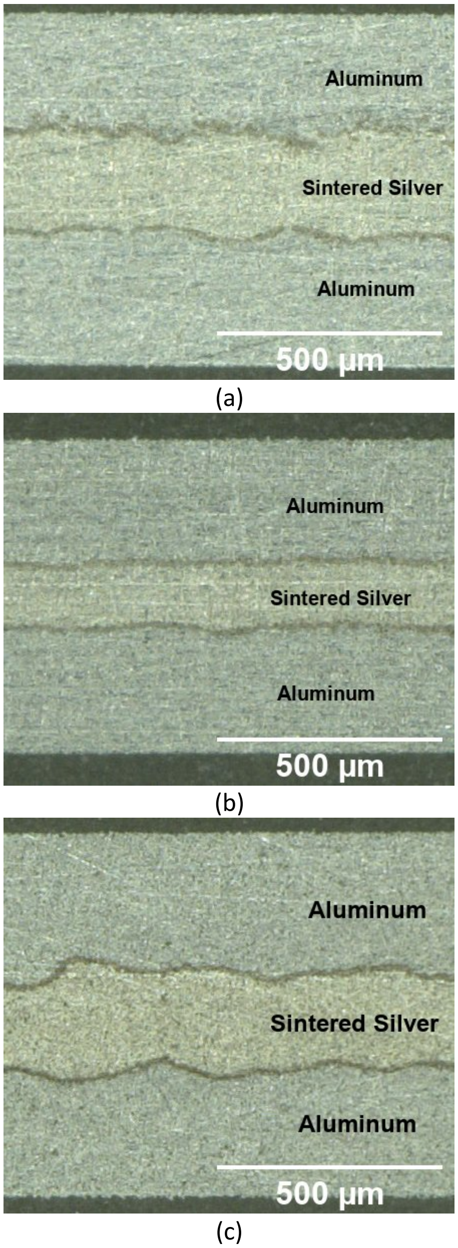


Fig. 6: Optical microscope images of cross-sections from nano-silver paste samples taken at 300 (a), 400 (b), and 500 (c), thermal cycles from –40 °C to 200 °C.

TABLE 1: MEAN SURFACE ROUGHNESS FOR SAMPLES CROSS-SECTIONED DURING THERMAL CYCLING.

Bonding Method	No. of Thermal Cycles	Mean Surface Roughness (µm)
Preform	300	4.59
	400	6.00
	500	5.26
Paste	300	9.97
	400	11.64
	500	11.28

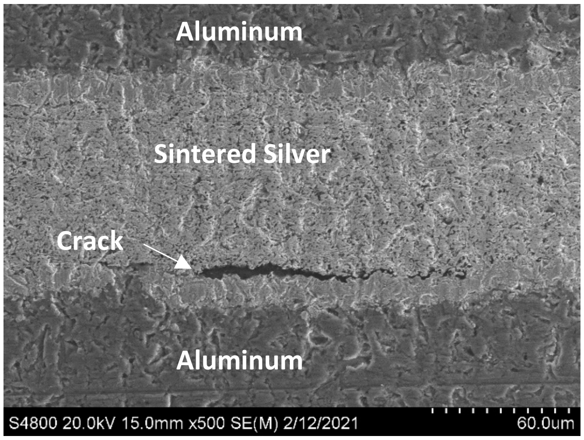


Fig. 7: SEM image of a multi-layer DBA sample after 500 thermal cycles from –40 °C to 200°C.

is a potential concern. Additionally, the bonding layer of the nano-silver paste samples is almost twice the thickness of the nano-silver preform. This will add additional thermal resistance to a critical path of the thermal impedance of a power module.

IV. THERMOMECHANICAL MODELING

A finite element analysis model was developed in ANSYS to compare the thermomechanical performance of the multi-layer substrates with other bonded samples. Previous work on reliability evaluation of micron-sized sintered silver bonded between a baseplate and DBC substrate reported failure at 2,300 cycles under a thermal cycling profile of -40 °C to 150 °C [15].

Fig. 8 compares the strain energy density per thermal cycle values for three different substrate configurations. The multi-layer or stacked substrate geometry analyzed in this investigation yielded a strain energy density per cycle value that is approximately ten times lower than the baseplate – DBC sample. While quantitative comparisons of lifetime are not possible, these results indicate a longer lifetime for the stacked substrates than the baseplate – DBC sample.

V. CONCLUSIONS

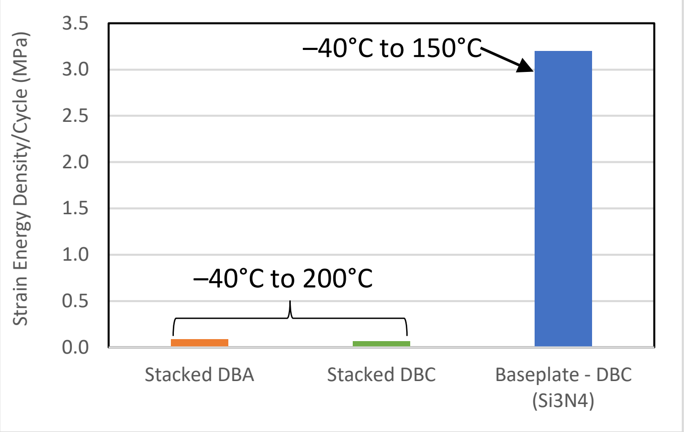


Fig. 8: Comparison of peak strain energy density per cycle for different substrate geometries in power modules.

Thermomechanical reliability of two large-area silver sintering methods for fabricating multi-layer DBA substrates are investigated. Samples thermally cycled from –40 °C to 200 °C were cross-sectioned and imaged, and no significant cracking or delamination was observed after 500 cycles. Some surface roughening of samples is observed, but with no increase in severity as compared to experiments performed on single DBA substrates [10], [12]. Results from this study indicate that multi-layer DBA substrates bonded with silver sintering have low voiding and defect density, and high reliability. Additionally, the silver-preform method is fast (60 seconds to transfer the preform, and 90 seconds to sinter), repeatable, and can achieve high bonding quality with low pressure (3 MPa). Accordingly, it is a promising solution for MV power modules. Substrates fabricated in this work will continue thermal cycling until clear failures of the sintered silver bond or ceramic substrate are observed.

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