Evaluating Dibenzyltoluene as a Dielectric Liquid for Encapsulation in High Voltage, High Power Density U(WBG) Power Electronics Modules

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Abstract— **The integration of (ultra) wide bandgap (UWBG) semiconductor technologies, such as silicon carbide and diamond, is crucial for the advancement of zero-emission vehicles (ZEVs), all-electric aircraft (AEA), and renewable energy systems. These technologies operate at higher temperatures, frequencies, and voltages, necessitating the development of novel materials that can endure these demanding conditions. Specifically, the polymeric encapsulation materials currently in use, such as silicone gel and epoxy resin, must be replaced with materials possessing superior properties in every aspect. This paper evaluates the suitability of dibenzyltoluene (DBT), a dielectric liquid, by assessing its thermal conductivity, viscosity, and dielectric breakdown strength under AC voltage. The effects of increased temperature on these properties are examined. Compared to room temperature, DBT exhibits minimal decline in both breakdown strength and thermal conductivity, which are crucial characteristics for insulating media in power modules. When these properties are compared to those of silicone gel, the superior performance of DBT becomes evident. This paper also briefly highlights the challenges to be considered when selecting a dielectric liquid, using the issues related to DBT as a reference.**

Keywords— (ultra) wide bandgap semiconductor, power electronics module, encapsulation material, zero-emission vehicles, dielectric liquid, dibenzyltoluene, dielectric strength

I. Introduction

In recent times, wide-bandgap (WBG) power semiconductors like silicon carbide (SiC) and gallium nitride (GaN), as well as ultra-wide-bandgap (UWBG) semiconductors such as aluminum nitride (AlN) and diamond, have gained substantial popularity for electric vehicle (EV) and zero-emission vehicle (ZEV) applications. These advanced devices offer significant advantages over traditional silicon (Si) semiconductors, including reduced power losses, higher switching speeds, greater breakdown voltage, and improved thermal performance [1-4]. Power electronics play a crucial role in addressing key challenges in the EV industry, such as efficiency, range, and cost, positioning WBG devices as a pivotal technology for the next generation of EVs. Integrating WBG devices into EV and ZEV power electronics can significantly enhance efficiency, reliability, and range.

Despite these benefits, challenges related to the packaging of power electronics modules persist. A significant limitation lies in the dielectric properties of the encapsulation materials, such as silicone gel (SG) and epoxy resin (EP), used within these modules, which are currently optimized for temperatures below 200°C. [5-12]. Silicone gel suffers from a high coefficient of thermal expansion (CTE), while epoxy resin suffers from high viscosity and low glass transition temperature, restricting their application to temperatures well below the desired range for (U)WBG power modules [13-16]. Although encapsulation materials based on mixtures of silicone gel and epoxy resin with micro- and nanoparticles have been proposed to increase operational capabilities, many challenges remain, as discussed in [1]. These issues include increased viscosity of the composite, interfacial defects, and the significant impact of filler concentration on the electrical, thermal, and mechanical properties. Therefore, a significant advancement in this field could be realized by using high-temperature dielectric liquids as insulating media, enhanced by their self-healing characteristics, low viscosity, and stable dielectric strength [17]. In this paper, dibenzyltoluene (DBT) is used as the dielectric liquid to measure the AC dielectric breakdown strength at two different temperatures. The viscosity and thermal conductivity (TC) of the liquid are measured at these two temperatures to evaluate the effect of temperature on these parameters. Similarly, the impact of temperature on the dielectric breakdown strength of the liquid is tested under repeated breakdown tests. The paper is organized into the following sections: Section II presents the detailed test setup and procedures for conducting the three tests; Section III presents the experimental results with a discussion for each; Section IV discusses some critical issues related to this dielectric liquid, which the authors believe are essential considerations for readers and future researchers in this area; and finally, the paper is concluded in Section V.

II. Test Setup and Procedure

A. Sample Preparation

The dielectric liquid selected for the experiment is Jarytherm Dibenzyltoluene (DBT), consisting of a mixture of dibenzyltoluene isomers. Manufactured by ARKEMA. DBT is primarily a high-temperature heat transfer fluid capable of operating within a wide temperature range (-40 to 350°C) without thermal decomposition [18-20]. According to the manufacturer's datasheet, it boasts high thermal stability (up to 350°C), a boiling point of 390.1°C, and a flash point of 212°C. Research on DBT for encapsulating power modules is limited, primarily because its primary application is heat transfer, and its dielectric characteristics are not well-documented. The required amount of DBT is poured into a testing cup for the experiment. This action creates air bubbles and voids on the surface, which have inferior properties compared to dielectric liquids, leading to a decrease in the liquid's dielectric strength. To eliminate these bubbles, the liquid is placed in a vacuum-drying oven for degassing at vacuum for 12 hours. Once degassed, the final sample is ready for use. If higher temperatures are needed, the sample can be heated in a high-temperature oven while continuously monitoring the temperature.

B. Electrode Arrangement

The test cell is constructed per the ASTM D877 standard, which specifies the test method for the dielectric breakdown voltage of insulating liquids using disk electrodes [21]. These electrodes are made of brass and have a diameter of 1 inch (25 mm). The outer cup is composed of a high dielectric strength material that is inert to any testing/cleaning liquids. It is designed to provide at least a 1-inch gap above the top electrode. The top electrode is the only adjustable component and can be repositioned to change the gap distance between the electrodes. This arrangement is preferred over actual power module packaging, where the substrate, metal electrodes, and liquid create a triple point (TP) because the compatibility of the liquid with substrates used in power modules is unknown. Testing according to the ASTM D877 standard provides a reference guideline for further research. For our experiment, the distance between the two electrodes is fixed at 2 mm.

C. Viscosity Measurement

As seen in Fig. 1, the SV-10 Vibro Viscometer from A&D Instruments is used to measure the viscosity of various dielectric fluids. This viscometer employs the tuning-fork vibration method, where an electromagnetic force drives two thin sensor plates. The electromagnetic drive maintains the sensor plates in constant amplitude oscillations. The current required to sustain these oscillations is directly correlated to the viscosity of the liquid.

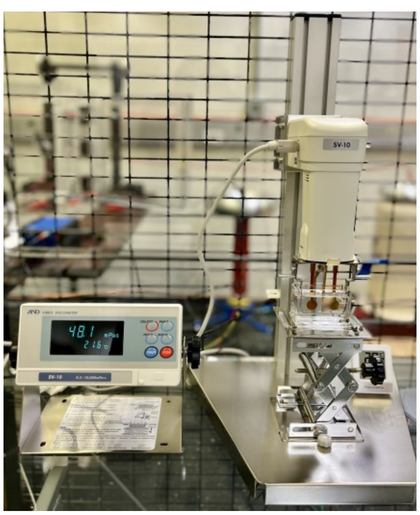

Fig. 1. Viscosity measurement of DBT at room temperature.

To measure the viscosity of the liquid, 45 ml is poured into the sample cup. The cup is then placed on the platform and gradually raised until both sensor plates are fully immersed in the liquid. Once the viscometer is started, the digital display will show the viscosity value and the corresponding temperature.

D. Thermal Conductivity Measurement

The thermal conductivity (TC) of DBT is unknown, as it is neither provided on the manufacturer's data sheet nor determined in previous research. However, TC is crucial in power module packages because high thermal conductivity ensures balanced temperatures within the module. Therefore, this paper measures the TC of the liquid at the two temperatures where the breakdown strength is determined. The TEMPOS thermal properties analyzer from the METER Group is used to measure the TC of the liquid. It consists of two main components: the TEMPOS controller and the sensor. To measure the TC of the DBT, the liquid is poured into a testing tube, and the sensor is inserted completely, ensuring there is at least a 5 mm gap around the sensor's needle to provide accurate measurements. The readings from the sensor are displayed on the controller, showing the conductivity value and the corresponding temperature.

E. Dielectric Strength Measurement

Traditional encapsulation materials, such as SG, have lower dielectric strength (around 17-20 kV/mm), which limits the operation of (U)WBG power module packages to lower voltages and electric fields. Additionally, their dielectric strength, along with other properties like viscosity and thermal conductivity, deteriorates rapidly at higher temperatures. The dielectric strength measurement setup comprises two main components: the testing chamber containing the liquid under examination and the high-voltage AC supply source. For the latter, an AC high voltage source, model 6CB100/50-7.5 rated at power frequencies, is used. It includes a control panel (CTRLPNL) and a high-voltage transformer (HV-XMER). This setup can generate up to 100 kV and deliver a maximum power of 7.5 kVA. The CTRLPNL features a human-machine interface (HMI) with a touchscreen display for controlling the status and test parameters. For our experiment, parameters such as overcurrent, overvoltage, dwell voltage, and voltage ramp rate are set to 5.0 mA, 85 kV, 80 kV, and 1 kV/s, respectively. The experiment was conducted with the testing cell placed inside a shielded room to minimize the impact of external factors. Fig. 2 shows the test setup.

III. Results and Discussion

A. Viscosity

One of the main challenges with current encapsulation materials, such as SG and EP, is their high viscosity. This high viscosity impedes the smooth flow of the encapsulant within power modules, leading to issues like void formation and defects at the encapsulant-substrate interface. These defects can reduce the dielectric strength of the encapsulant and result in premature failure. To assess the impact of temperature on the viscosity of DBT, its viscosity was measured at two different temperatures: room temperature (21°C) and 42°C. The viscosity of DBT at room temperature is 48.1 mPa·s. For comparison, SG has a viscosity ranging from 400 to 500 mPa·s at room temperature before curing (e.g., Sylgard 527 A&B [22]). After curing, SG forms a gel-like structure with even higher viscosity.

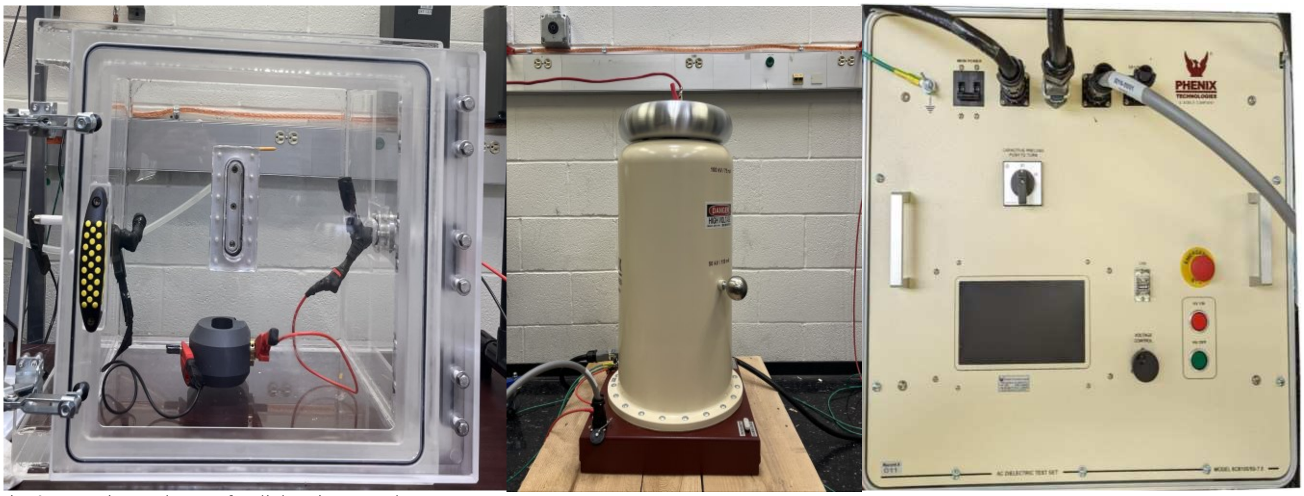

Fig. 2. Experimental setup for dielectric strength measurement.

When the temperature is increased to 42°C, the viscosity of DBT decreases to 17.8 mPa·s. The kinematic viscosity is calculated by dividing the viscometer's reading by the liquid's density. With the liquid's density at approximately 1.044 g/cm³ at 21°C and 1.029 g/cm³ at 42°C, the kinematic viscosity values are 46.07 mm²/s and 17.3 mm²/s, respectively. This decrease in viscosity with increasing temperature is typical for liquids. The molecules gain more kinetic energy at higher temperatures, allowing them to move more freely and overcome the intermolecular forces contributing to viscosity. The lower density at higher temperatures also results in fewer molecular interactions per unit volume, contributing to reduced viscosity.

B. *Thermal Conductivity*

Although ceramic substrates are the primary medium for heat dissipation in power modules, dielectric liquids with high thermal conductivity (TC) are crucial in ensuring uniform temperature distribution across the module. This helps reduce thermal stress and potential damage caused by thermal cycling. A dielectric liquid with high TC efficiently transfers heat away from active components such as IGBTs and diodes to the heat sink, making high TC a desirable property for encapsulation materials. Additionally, minimal TC degradation with increasing temperature is essential.

Three readings were taken at each temperature to ensure accurate TC measurements, and the TC values are presented as the average of these readings, Fig. 3. At room temperature, the measured thermal conductivity values are 0.311, 0.3099, and 0.3099 W/m-K, with an average value of 0.3103 W/m-K. This value is notably higher compared to SG and other dielectric liquids like mineral oil, silicone oil, and ester oils [23], as indicated in Table I.

When the temperature was increased to 42°C, the average TC from the three readings was 0.2921 W/m-K. This represents a relatively stable value, with only about a 5% reduction despite the temperature doubling, suggesting minimal thermal degradation of DBT at higher temperatures. The temperature fluctuation throughout the experiment was less than 1°C, ensuring precise readings.

TABLE I. THERMAL CONDUCTIVITY OF BDT COMPARED TO OTHER MATERIALS.

Insulating material	**Thermal conductivity (W/m-K) at room temp.**
DBT (This experiment)	0.3103
Silicone gel	0.15-0.17
Silicone oil	0.15
Synthetic ester oil	0.15
Mineral oil	0.11-0.16
Vegetable oil	0.16-0.17

Fig. 3. Thermal conductivity measurement: (a) sensor. (b) controller.

C. *Dielectric Breakdown Strength*

To conduct the breakdown experiments on the liquid, the distance between the two-disc electrodes was fixed at 2 mm. The AC voltage was increased automatically at a rate of 1 kV/s and the voltage at which the breakdown occurred was recorded. The breakdown within the liquid was indicated by a hissing noise and a visible spark, as shown in Fig. 4, confirming the breakdown between the electrodes. Three breakdown voltage values were recorded at each temperature.

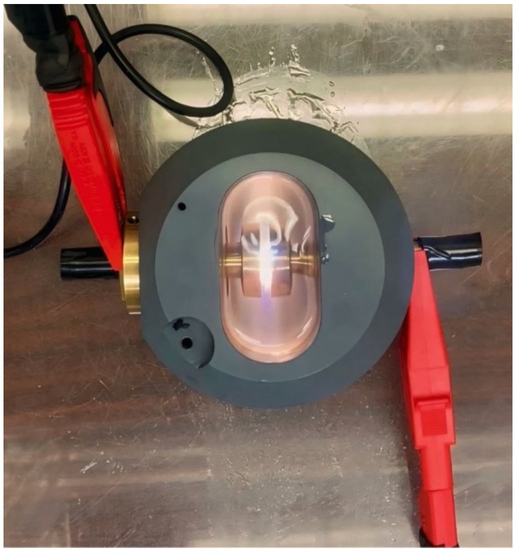

Fig. 4. Complete breakdown of DBT between two disc electrodes.

A key advantage of using this AC voltage generator is its capability to rapidly shut down within microseconds after a breakdown event, minimizing potential damage to the liquid. Dielectric liquids possess self-healing properties, meaning they can recover from breakdown damage within a few minutes. This allows for the completion of three experiments at each temperature without the need to replace the liquid. The same procedure was followed at 42°C to assess the effect of temperature on the liquid's breakdown voltage. The breakdown voltage values and corresponding dielectric strength at both temperatures are presented in Table II.

TABLE II. AC BREAKDOWN VOLTAGE AND DIELECTRIC STRENGTH OF DBT AT THE TWO TEMPERATURES.

Electrodes gap	Temperature	Breakdown number	AC Breakdown voltage (kV)	Dielectric strength (kV/mm)
2.0 mm	21°C	1	53.9	107.8
		2	53.7	107.4
		3	50.9	101.8
	42°C	1	57.1	114.2
		2	55.1	110.2
		3	46.1	92.2

Notably, the initial breakdown tests at elevated temperatures reveal a higher breakdown voltage for DBT, as indicated by Table II. This significant observation is in line with previous experiments, which have also concluded that DBT demonstrates superior streamer and partial discharge inhibition properties at higher temperatures [24]. However, when the breakdown experiment was repeated with the same sample after a few minutes' intervals, the reduction in breakdown voltage was 5.6% at room temperature and 19% at 42°C. This may indicate that the liquid takes longer to self-heal at higher temperatures or that its breakdown characteristics degrade more noticeably with repeated breakdown tests, especially at higher temperatures. This trend is consistent with previous experiments showing that the breakdown voltage of DBT and other dielectric liquids decreases with temperature [20].

Despite this, DBT demonstrates excellent dielectric strength compared to other encapsulation materials, as the reduction in breakdown voltage is relatively low. The low viscosity of the liquid at higher temperatures and the resulting intense liquid flow, which can lead to electrohydrodynamic (EHD) motion, help rapidly expel breakdown by-products. This could help maintain stable dielectric strength even at higher temperatures. This is particularly desirable for use in (U)WBG power modules utilized in zero-emission vehicles (ZEV), which are subjected to very high electric fields and temperatures. High electric field stress and thermal stress are the two primary challenges faced by power modules. Mitigating these issues is essential for ensuring their reliable and long-lasting operation. However, further testing under thermal aging is necessary to determine how these conditions affect the liquid's properties.

In conclusion, the stable dielectric strength of DBT, with a maximum dielectric breakdown strength of 107.8 kV/mm at 21°C and 114.2 kV/mm at 42 °C, and an average dielectric strength of 105.7 kV/mm and 105.5 kV/mm, respectively, across three experiments, underscores its potential as an encapsulation material in (U)WBG power modules. Further research at even higher temperatures could provide more insights into the dielectric characteristics of the liquid.

IV. ISSUES RELATED TO THE USE OF DBT

These properties of DBT—low viscosity, high thermal conductivity, and high dielectric breakdown strength—are undoubtedly beneficial. Low viscosity allows the liquid to flow easily within the module, minimizing defect formation at material interfaces and facilitating rapid heat removal. High thermal conductivity is essential given the heat transfer requirements of encapsulation materials. Additionally, high dielectric strength ensures the liquid can withstand high electric field stress for extended periods. However, certain issues must be addressed before selecting any material for encapsulation in power electronics modules for zero-emission vehicles (ZEV). This section discusses some of the challenges associated with DBT in this context.

One major concern with the liquid is its inclusion on the US Toxic Substances Control Act (TSCA) list, which compiles all chemicals and materials deemed harmful to the environment [25]. In light of global efforts to achieve zero emissions by 2050 through the widespread adoption of green energy, smart grids, zero-emission vehicles (ZEVs), and all-electric aircraft (AEAs), it is imperative that the insulating medium used in power electronics modules be environmentally friendly. However, it is important to note that Jarytherm DBT is non-biodegradable and presents risks to both the working environment and personnel if advanced precautions are not implemented. The liquid is toxic to aquatic life and is known to have long-lasting detrimental effects. Therefore, it is also listed as a marine pollutant in the International Maritime Dangerous Goods Code (IMDG) [26]. In laboratory environments, failure to isolate and adequately ventilate high-temperature experiments with this liquid can result in the release of vapors that can lead to breathing difficulties and pose significant risks to the environment.

Furthermore, when subjected to high heat, the liquid undergoes decomposition, liberating toxic gases. This was demonstrated during experiments conducted at a temperature of 100°C, at which point the liquid emitted a potent odor. This temperature is well below the boiling point (390°C) and flash point (212°C) of DBT. While the use of full-face respirator masks can mitigate exposure to this odor, it remains hazardous to the surrounding environment and individuals in close proximity.

However, the significantly superior properties of this liquid compared to current encapsulation materials warrant a thorough evaluation of its eco-friendliness. As the world moves towards (U)WBG power electronics modules to achieve net-zero emissions, it is crucial to use materials like this as insulating media. If this material is to be used in research environments, its toxicity must be considered for safety reasons. In conclusion, these characteristics highlight the need for careful consideration, comprehensive safety measures, and strong oversight in any setting where this specific liquid is employed.

V. Conclusion

This study demonstrates the feasibility of using dibenzyltoluene (DBT) as a dielectric liquid for high-voltage, high-power density (U)WBG power electronics modules, making it suitable for implementation in zero-emission vehicles (ZEV) and other similar applications. The experimental results show that DBT maintains a high dielectric breakdown strength and lower viscosity at elevated temperatures, which are critical properties for enhancing the performance and reliability of power modules in electric vehicles. The stable thermal conductivity of DBT further supports its suitability for effective heat dissipation in these applications. DBT proves to be a superior encapsulation material in all three analyzed aspects—viscosity, thermal conductivity, and breakdown strength—compared to silicone gel, the most widely used encapsulant today. However, the environmental impact and safety hazards associated with DBT, such as its toxicity and non-biodegradability, pose significant challenges that must be addressed before widespread adoption. Future research should focus on developing environmentally friendly alternatives or mitigating the risks associated with DBT to fully leverage its potential benefits in (U)WBG power module encapsulation.

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