A Comprehensive Evaluation of Al Heavy Wire Bonding and Ribbon Bonding Application in high power WBG Power Modules

Yang Li¹, Mustafeez Hassan¹, Yuxuan Wu¹, Asif Imran Emon¹, Shiyue Deng¹, Fang Luo¹, Amol Deshpande², Michael McKeown³

¹Department of Electrical & Computer Engineering, Stony Brook University
Stony Brook, NY 11794, USA
²Wolfspeed, Inc.
Fayetteville, Arkansas, 72701, USA
³Hesse Mechatronics
116 Ellsworth Avenue, Mineola NY 11501, USA
Email: Yang.li.9@stonybrook.edu

Abstract
Targeting at a comprehensive Multiphysics evaluation for Al wire and ribbon bonding technologies for WBG power module, this paper investigates and compares the stray inductance, heat dissipation and fatigue life between these two bonding schemes in an XHP packaging designed in house. During calculation, it was tried to keep equivalent volume for the Al ribbon when substituting local Al wires for fair comparison. Results of stray inductance show extremely limit bonding-type dependence in ranges from 1 kHz to 10 MHz, and further expanding ribbon size to varied levels still presents negligible impact. The two bonding technologies do not prove their capability in sharing either static or transient thermal loads when the baseplate bottom is efficiently liquid cooled. Detailed study confirms that heat dissipates dominantly in vertical direction to the Cu baseplate rather than through Al bonds. Ultimately, the only noticeable benefit of Al ribbon in our multiscale analysis is its improved reliability during temperature cycling, with data supporting a 2.17× times longer lifetime of Al ribbon when comparing to its Al wire counterpart.

Key words
WBG power module, heavy Al wire and ribbon, electrical-thermal-mechanical Multiphysics evaluation

I. Introduction
The typical application fields for high power wide bandgap (WBG) power modules are for power grids, wind turbines and electrical vehicles. WBG power modules are utilized for the purpose of power conversion and transmission. With voltage rating from hundreds to over tens of thousands of volts and current rating over hundreds of amps, together with the demand for compact design and higher power density; researchers and designers are constantly targeting at innovated packaging schemes together with advanced material systems. One of the efforts that has been practiced is the adoption of aluminum (Al) ribbon bonding to replace conventional heavy Al wire bonding as interconnections between chip and substrate.

Different literature [1]-[4] have compared their benefits and limitations in terms of their thermomechanical reliability, as well as its corresponding impact on the system. However, from the power module packaging and application perspective, their consideration limits to thermomechanical reliability only. This paper is intended to have a comprehensive comparison between these two technologies regarding their impact on stray inductance and thermal management of the power module, as well as their thermomechanical reliability under varied mission profiles. In this paper, the author will first introduce the geometry and material of the power module. Electrical parameters as parasitic inductance from both ribbon bonded and wire bonded structures will be presented in Part III, and after that comes the comparison of their thermal performance in both static and transient states. Part V of this paper follows with the evaluation of thermomechanical behavior and prediction of fatigue life for both the types of bonding techniques during temperature cycling load. Finally, Part VI concludes the key findings during those comprehensive analyses.

II. Module configuration
The power module for analysis in this study is designed in house for high power application and conforms to the standard Infineon XHP package layout. Here both the pin outline and footprint of this design match the commercial
XHP module. Electrically it is a half-bridge topology module with multichip paralleling layout that positions four chips at each switching position, therefore it encloses eight devices in total. For this design we select bare SiC MOSFETs from GeneSiC and target for 3.3 kV, 200 A application with targeted switching frequency of 80-100 kHz. Furthermore, the gate-driver circuit is also included inside the package to optimize the performance of this power module.

For package structure, Fig. 1(a) introduces the 3D construction of the module package which is 140 × 100 ×40 mm, while (b) shows its internal layout with removed external housing. The SiC MOSFETs are from GeneSiC (GR40MT33) and they are vertical devices with drain at the chip bottom and source as well gate at the chip top. The bottom of the devices, the drains, is designed to be reflow soldered to Cu patterns on Direct Bonded Copper (DBC) substrate by SAC305 solder paste, while the top of the devices, the source and the gate, is either Al ribbon or Al wire bonded to another Cu pattern on DBC in order to complete the half-bridge circuit. External power is communicated through laminated Cu busbars which are screw connected to Cu terminals soldered onto Cu of DBC substrate. The whole design is mechanically and thermally supported by Cu base plate and ultimately housed by plastic case after gel sealing of the internal components and connections.

Fig. 2(a) shows the top view of the internal layout where the bonding wires are presented after hiding the top PCBs and Cu bus bars, while Fig 2(b) lists typical dimensions of the wires that connect the top surface of devices and Cu layer on DBC. In the following studies, the Al wires will be analyzed first and then replaced with Al ribbons for direct comparison regarding to their influence on stray inductance, thermal performance in varied conditions and ultimately thermomechanical reliability during temperature cycling.

### III. Comparison of parasitic inductance

Targeting at high power and high switching frequency applications, this SiC power module is sensitive to its loop stray inductance as it would impact voltage overshoot and switching oscillation which in turn increases additional device stress, switching speed and switching power loss.
Here the module is first designed in SOLIDWORKS and then imported into ANSYS Q3D software to extract parasitic inductance.

A. Model setup

During simulation, the internal DC bus bar, DBC copper pattern, devices and Al bonding in the power loop are all included in the analysis and their accumulated stray inductance in the overall loop was estimated. Gate wires, PCBs and base plate are eliminated as they barely contribute to stray inductance in the power loop. Excitation sites of source and sink in the simulation are applied at internal circular wall of M3 screw terminals at DC+ and DC- respectively for LD1S2 extraction. Wire layout is shown in Fig. 2(a) and is with 0.3mm thickness for all Al wires, and later are replaced with Al ribbons shown in Fig. 3(a). It is worth noting that during wire replacing process, both loop height and shape were maintained constant. However local Al wires were combined into one equivalent Al ribbon so to maintain the volume of Al unchanged, as illustrated in Fig. 3(b). Here four local wires with 0.3mm × 0.3mm each ultimately formed one ribbon with 0.3mm × 1.2mm in size.

B. Results and discussion

The calculated inductance for $L_{D1S2}$ is 29.87 nH for module with Al wires at 1 kHz, while it is 30.5 nH for module with Al ribbons at the same frequency. Checking at different frequencies, the results do not present obvious frequency dependence up to 10 MHz and this 2.1% difference between the two bonding types is within calculation tolerance from model processing in simulation, such as local mesh size with local feature layout. In this sense, it can be concluded that transferring to Al ribbon with equivalent volume as for the local wires would not impact inductance in the power loop. Considering availability of ribbon sizes from vendors in the market and as an extension of this parasitic study, analysis was carried with varied ribbon lengths and have listed the results in Table 1. With very limited effect when changing bonding size, Al ribbon bond is proved to be a negligible factor in the power loop parasitic inductance. Hence that optimizing stray inductance for this power module aiming at MHz class application should probably not consider optimization of the Al bonds.

Table 1. Stray inductance for two bonding techniques.

<table>
<thead>
<tr>
<th>Bond size (mm)</th>
<th>Stray inductance (nH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al wire bond</td>
<td>0.3 × 0.3</td>
</tr>
<tr>
<td></td>
<td>0.3 × 1.2</td>
</tr>
<tr>
<td>Al ribbon bond</td>
<td>0.3 × 1.5</td>
</tr>
<tr>
<td></td>
<td>0.3 × 1.75</td>
</tr>
<tr>
<td></td>
<td>0.3 × 2.0</td>
</tr>
</tbody>
</table>

IV. Comparison of thermal performance

A. Model setup

The evaluation of the impact of two bonding technologies on thermal performance of this power module is completed in ANSYS Workbench. For thermal analysis this model includes busbars, Cu terminals, SiC devices, Al bonds, DBCs and also the underneath Cu base plate into calculation. Al wires are still with 0.3mm × 0.3mm and Al ribbons are with 1.2mm × 0.3mm which is equal to the local four wire bonds volume-wise, as shown in Fig. 3(b). Thermal properties for each material are listed in Table 2. Checking in mesh metric graph, meshing is dominant by 20-node hexagonal element with negligible amount of 15-node wedge elements. Mesh settings are assigned identical for both Al-wire and Al-ribbon.
structures for meaningful comparison. Fig. 4 shows the final meshing graphs for both.

![Meshing details with (a) Al wire bonds and (b) Al ribbon bonds for thermal analysis](image)

**A-1: Static analysis**

The two structures are imported for static thermal analysis first. During calculation the ambient temperature is set at 25°C and heat convection is applied at the bottom surface of the Cu base plate with convection coefficient 4000 W/m²·°C resembling liquid cooling condition. Considering rated current at power factor= 0.8, modulation index D= 0.5 and switching frequency f_sw=100 kHz, the power loss for individual MOSFET has been calculated. Therefore, the channel current during turn-on is set at I= 50 A, while R_DS_on and energy losses for both turn-on and turn-off are obtained directly from device datasheet. As a result, conduction loss is calculated as 50 W (I²× R_DS_on × D) and switching loss is calculated as 99.1 W ((E_on+ E_off)× f_sw). Adding the two yields the total power loss to be 149.1 W, which is applied to the top surface of each individual chip for further evaluation.

**A-2: Transient analysis**

Since, during field application, pulsating current applies as a general condition in power switches, we studied its influence on transient thermal behavior for both bonding types as well. Similarly, the ambient temperature is set at 25°C and heat convection is applied at the bottom surface of the Cu base plate with convection coefficient of 4000 W/m²·°C resembling liquid cooling condition. In the reason that the maximum pulsed drain current designed for this GeneSiC device is around four times higher than its continuous drain current, we assume a pulsed current of 250 A which results in instantaneous power loss of 2500 W for each SiC MOSFET. There are two pulses applied to this system with each last 5 milliseconds. Detailed curve of power loss is plotted in Fig. 6. Material density and heat capacitance data for transient study can be referred to Table 2.

**B. Results and discussion**

**B-1: Static thermal performance**

The ultimate temperature distribution is presented in Fig. 5 (a) and (b). The two contours are identical and with negligible difference between the maximum junction temperature on chips which shows around 98.8°C for both. Moreover, heat dissipates directly through vertical direction to the base plate rather than through the Al bonds horizontally. This is further confirmed by another simulation where Al bonds are all removed, shown in Fig. 5(c), and hence confirms no effect on static thermal performance from Al bonds. With this data, it can be concluded that Al ribbon bonding fails to offer noticeable advantage over Al wire bonding during continuous operation. This also indicates that efforts on optimization according to parametric analysis on bonding distance, loop shape and height would not yield favorable result at least for this package design.

**B-2: Transient thermal performance**

Plot of maximum junction temperature Tj with time is posted in Fig. 7 for both bonding types and here the two curves are completely overlapping with imperceptible difference. Fig. 8 reveals the temperature contour of both. From cross sectional images, it was observed that heat dissipation travels majorly through vertical direction and stops around the interface between DBC and the Cu baseplate within the given heat loss and pulsating time. Moreover, neither did the Al wire nor ribbon bond succeed in help transferring the thermal loading to neighboring structures. Therefore, similarly as for the static case, it wasn’t observed that the Al bonds took obvious responsibility under this transient thermal loading condition, and hence no difference was observed between the two.
bonding technologies.

The authors did notice that multiple sources [6]-[8] claimed that Al ribbon owns the benefit of improved heat dissipation, and here we would attribute such discrepancy to their applications where the local equivalent volume of Al ribbon being larger than that of local Al wires [7], and also possibly to their specific package design and thermal mission profile in different conditions [6, 8].

For both static and transient studies, the benefits from thermal perspective after transitioning to Al ribbon bonds are not observed. This is expected since in both cases they have equivalent cross-section area and also identical material thermal conductivity which reasons that the thermal resistances should be the same for both connection types.

Figure 5. Static thermal results with (a) Al wire bonds (b) Al ribbon bonds and (c) all bonds removed.

Figure 6. Power loss vs. Time for transient analysis.

Figure 7. Evolvement of Tj with pulsating loads and time for both Al wire and ribbon bonding.
Figure 8. Transient thermal results at the final state with (a) Al wire bonds and (b) Al ribbon bonds. Their cross-section images are also shown at local bonding positions.

V. Comparison of thermomechanical fatigue life

Understanding that neck/heel crack as dominant failure modes for Al connection during cyclic loading, we compare the reliability of heavy Al wire and Al ribbon within the same packaging structure under given thermomechanical condition. Again, the ribbon which replaced local wires is with equivalent in volume as for those wires in order to provide a fair comparison.

A. Model setup

ANSYS Workbench Mechanical is used for this temperature cycling analysis. In this study we’ve taken SiC devices, Al bonds, DBC and the Cu base plate into calculation. Since in this sense this structure present itself as an axis-symmetric design, 1/4 model is used in order to facilitate faster calculation while maintaining result accuracy. Mesh is dominated by 20-node hexagons and refined sizes are assigned for wire/ribbon and SiC device. Final meshing and localized detailed mesh are shown in Fig. 9. Material properties can be referred to Table 2 where constitutional equation for aluminum is assigned as multilinear kinematic hardening which is obtained from uniaxial tensile tests [5].

Figure 9. 1/4 meshed model for TC analysis. (a) Al wire and (b) Al ribbon

In the simulation the temperature profile follows JEDEC JESD22-A104D standard and its curve is shown in Fig. 10.

<table>
<thead>
<tr>
<th>Material properties</th>
<th>SiC</th>
<th>AlN</th>
<th>Cu</th>
<th>Al wire/ribbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>E (GPa)</td>
<td>169</td>
<td>310</td>
<td>117</td>
<td>68.9</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.23</td>
<td>0.24</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>CTE (10^{-6}/K)</td>
<td>3</td>
<td>5.6</td>
<td>16.12</td>
<td>20</td>
</tr>
<tr>
<td>k (W/m K)</td>
<td>370</td>
<td>190</td>
<td>390</td>
<td>210</td>
</tr>
<tr>
<td>ρ (kg/m^3)</td>
<td>3210</td>
<td>3300</td>
<td>8933</td>
<td>2700</td>
</tr>
<tr>
<td>C (J/kg K)</td>
<td>750</td>
<td>740</td>
<td>385</td>
<td>900</td>
</tr>
<tr>
<td>Yield stress (MPa)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>150</td>
</tr>
<tr>
<td>Plasticity</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Multilinear kinematic hardening [5]</td>
</tr>
</tbody>
</table>
This thermal cycling ranges from -65°C to 150°C and experiences one cycler per hour with 15 min ramping time and 15 min dwell time at both the peak and bottom. Evaluations have proved that generally after 3-5 cycles the value of accumulated plastic strain will reach stabilized state and hence, we assigned 5 cycles in this analysis.

![Temperature profile](image)

**Figure 10. Temperature profile during TC**

B. Results and discussion

General Coffin-Manson equation, given in Equation (1), for estimating number of cycles to failure for metals experiencing cyclic plastic deformation is used here for evaluating TC life time for Al wire/ribbon. Here $\varepsilon_{pt}$ is the accumulated plastic strain in the damaged region, while C1 and C2 are linearly fitted constants based on fatigue test and are set to $C1=16.55$ and $C2=1.83$ for heavy Al wires [9], which is assumed to be the same for Al ribbon with the variation of material microstructure and defect density being neglected.

$$N_f = C_1 \cdot \varepsilon_{pt}^{-C_2} \quad (1)$$

After visually inspecting the results of plastic strain over the global model and hence pinching out high strain area as well as its thickness, we determined to slice the bonds at a thickness of 37.5 um away from DBC to estimate with a better accuracy on its accumulated plastic strain. Here $\varepsilon_{pt}$ is obtained by volume weighted average (VWA) method as

$$\varepsilon_{pt} = \frac{\sum_j \varepsilon_{ptj} V_j}{V_{total}} \quad (2)$$

where $V_{total}$ the total volume of all elements around the damage region, $V_j$ the volume of the $j^{th}$ element, and $\varepsilon_{ptj}$ the associated accumulated plastic strain. ANSYS output parameter (NL, EPEQ) offers the accumulated plastic strain and is averaged based on element by post processing session with the assistance of ETABLE commands [10]. Here the volume and $\varepsilon_{pt}$ for each targeted element will be listed in the Solver Output for further analysis.

The maximum $\varepsilon_{pt}$ for both bonding techniques occurs at the chip side at Al-chip interface, as shown in Fig. 11. Being the critical crack initiation site, the element that has the maximum $\varepsilon_{pt}$, together with all its neighboring elements that share at least one common boundary with this element are taken account into $\varepsilon_{pt}$ calculation.

![Accumulated plastic strain](image)

**Figure 11. Accumulated plastic strain for module with (a) heavy Al wire and (b) Al ribbon bonds.**

As results, the calculated $\varepsilon_{pt}$ for heavy Al wire is $1.09E-5$, yielding a TC lifetime of 576 cycles, while the calculated $\varepsilon_{pt}$ for Al ribbon is $2.24E-4$, suggesting a TC lifetime of 1250 cycles, roughly $2.17\times$ times higher. This obvious enhancement is probably benefited from the larger interconnecting area which assists the ribbon in becoming more adaptive to large plastic deformations from CTE mismatch of materials. This improvement achieved from the ribbon bonds on fatigue reliability are also in concordance with other literatures who have claimed similar conclusion [1], [11], [12].

VI. Conclusion

This paper targets at a WBG power module that comes with two bonding techniques: heavy Al wire and Al ribbon. Using this module as a vehicle for analysis, we have studied comprehensively the effect of bonding techniques on its electrical, thermal and thermomechanical performance. The
analysis is completed by FEA method on multi-physics level. Within our scoped range, the stray inductance for this power loop is hardly impacted after transitioning to Al ribbon from Al wire. This holds true not only for the ribbons with equivalent volume when combining that of the local wires, but also when the ribbons are with larger cross sections by extending its length to varied levels.

For static and transient thermal performance, when massive cooling is applied such as efficient liquid cooling, Al wires/ribbons could hardly contribute their effort on heat dissipation. This was proved by removing all bond connections while keeping other parts in simulation untouched, since any thermal deterioration in this case is not proved. This in turn indicates that the effect of Al bonds in either form on heat removal is negligible. This conclusion sounds reasonable in that in both cases they have equivalent cross-section area as well identical thermal conductivity which leads to same thermal resistance for both connection types. Therefore, optimization based on parametric study focusing on loop distance/shape/height for improved thermal performance would probably end in futile efforts.

In case of thermomechanical fatigue life, Al ribbon is predicted to be $2.17 \times$ higher than that of Al wire. Maximum strain present itself at the Al-SiC interface which indicates that crack will initiate in Al at the chip side. This could be attributed to the larger contact area for the ribbon version would help in absorbing large deformations and hence yielding a smaller accumulated plastic strain during TC. This conclusion is in accord with simulation and/or testing results from other literatures.

References


