Properties of a GaAs Power Rectifier Diode Module for Ultra-Fast Electric Vehicle Battery Charging Systems

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1. Motivation

Gallium Arsenide (GaAs) power diodes with a low forward voltage drop of $V_f = 1.3$ volt at 15 ampere have recently been proposed. We integrated these diodes in a silver and copper sintered EconoPACK 2 power module copper and investigated the
- typical electrical performance of these diodes in an LLC converters for ultra-fast battery charging
- thermal characteristics of the power module and
- large area low temperature copper sintering behavior, when sintering submodules onto the baseplate

2. Introduction

GaAs is well established in ultra-fast signal processing and in infrared sensor devices (e.g. in mobiles). GaAs has
- a bandgap of 1.42 eV (slightly higher than Si: 1.12 eV)
- a low thermal conductivity of about 33 W/mK at 100 °C
- an electron mobility of 8500 cm²/(V*s), six times higher compared to Si

Higher blocking voltage than silicon
Thermal design and cooling more demanding compared to silicon or SiC power modules
Reduced switching losses, as stored charge is inversely proportional to mobility

$$Q_f = \frac{I_f \cdot W^2}{V_{\text{drift}} \cdot (\mu_n + \mu_p)}$$

3. System Design

The LLC converter belongs to the Zero Voltage Switching topologies, resulting in
- reduced switching losses and reduced EMI
- small gate driver source capability (no miller effect at turn on)
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4. Packaging

As the thermal conductivity of GaAs is quite low with 33 W/mK at 100°C, the thermal conductivity of the module must be high. We built up a module with high thermal conductivity by using silver sinter paste for die attachment and copper sinter paste for the sub-module (half bridge, diode rectifier) attachment. For high module robustness we used:

- a thick film copper substrate with 350 µm thick Cu layers (top + bottom)
- a 635 µm thick zirconia toughened alumina substrate (ZTA)

For a first fundamental insight into the pressure sinter behavior of low temperature copper sinter pastes under N₂, we investigated the:

- die shear behavior of 2.3 x 2.3 mm² dies
- large area sintering of 24 x 32 mm² ZTA sub modules onto the 3 mm thick base plate of the module

5. Results: Thermal and electrical evaluation

Thermal module resistance

- Set A: base plate temperature: 75 °C, 30 W, GaAs thickness 580 µm
  \[ R_{\text{th, module}} = 0.73 \text{ K/W}, T_{J-\text{GaAs}} = 97°C \]
- Set B: base plate temperature: 75 °C, 30 W, GaAs thickness 70 µm
  \[ R_{\text{th, module}} = 0.33 \text{ K/W}, T_{J-\text{GaAs}} = 85°C \]

Efficiency of air-cooled LLC converter

- Configuration A – All SiC
  
  Max. efficiency at 850 W Output: 97.7%

- Configuration C – GaAs free wheeling
  
  Max. efficiency at 1200 W Output: 99.3%

GaAs characteristic values

- Forward voltage drop at RT and 100 °C
  
  - Vf (RT) = 1.5 V
  - Vf (100 °C) = 2.0 V

- Reverse blocking behavior at RT and 100 °C
  
  - Vr (RT) = 600 V
  - Vr (100 °C) = 450 V

6. Conclusion

- Using additional GaAs diodes instead of internal SiC body diodes increases the max. efficiency of the LLC converter by 1.6%.
- Reliable large area low temperature Cu pressure sintering could be demonstrated up to a substrate size of 24 x 32 mm² on 3 mm thick base plates.
- Shear values of 2.3 x 2.3 mm² measuring dies sintered by low temperature Cu sinter pastes can exceed 70 MPa, depending on the sinter parameters.
- Thinning the GaAs diodes is recommended as the thermal resistance of the module can be lowered by a factor of two and the stored charge is further reduced.