Design, Analysis, and Experimental Verification of a Mechanically Compliant Interface for Fabricating Reliable, Double-Side Cooled, High-Temperature, Sintered Silver Interconnected Power Modules

David W. Berry

Dissertation submitted to the faculty of Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
In
Materials Science and Engineering

Guo-Quan Lu, Chair
Khai D.T. Ngo, Co-chair
Alex O. Aning
Louis J. Guido

August 13th, 2014
Blacksburg, Virginia

Keywords: Three-dimensional packaging, double-side cooled, planar, power module packaging, thermal resistance, thermal impedance, sintered silver, quarter-bridge, half-bridge.

Copyright 2014, David W. Berry
Name: David Berry
Job Title: Graduate Student
Institution: Virginia Tech Department of Materials Science and Engineering
Title of Work Used: Transient liquid phase (TLP) bonding for microsystem packaging applications
Publication Status: Published
Publisher: Solid-State Sensors, Actuators and Microsystems, 2005
Publication Year: 2005
Description of Work: journal article
Date of Evaluation: May 19, 2014
Date of Intended Use: May 19, 2014

Describe the Purpose and Character of Your Intended Use:

[+] Use is for "criticism, comment, news reporting, teaching, (including multiple print copies for classroom use), scholarship or research"
Describe the **Nature** of Your Intended Use of the Copyrighted Work:

[+] Work to be used has been previously PUBLISHED

Describe the **Amount** of Your Intended Use in Relation to the Copyrighted Work as a Whole:

[+] Only limited and reasonable portions will be used

Describe the **Effect** of Your Intended Use on the Potential Market or Value of the Copyrighted Work:

[+] Proper attribution will be given with the intended use
The Average "Fairness Level," Based on Your Rating of Each of the 4

Factors, Is:

[see tool disclaimer for important clarifying information]:

Fair Unfair

Based on the information and justification I have provided above, I, David Berry, am asserting this use is FAIR under Section 107 of the U.S. Copyright Code.

Signature: David Berry
Date of Signature: 5/20/14

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Name: David Berry
Job Title: Graduate Student
Institution: Virginia Polytechnic Institute and State University
Title of Work Used: Reliability assessment of sintered nano-silver die attachment for power semiconductors
Copyright Holder: M. Knoerr, S. Kraft, and A. Schletz
Publication Status: Published
Publisher: Electronics Packaging Technology Conference (EPTC)
Place of Publication: Electronics Packaging Technology Conference (EPTC)
Publication Year: 2010
Description of Work: Reliability assessment of sintered nano-silver die attachment for power semiconductors
Date of Evaluation: August 21, 2014
Date of Intended Use: August 21, 2014

Describe the **Purpose** and Character of Your Intended Use:

[+] Use is clearly defined and is restricted in scope (limited duration, not iterative, restricted access, etc.)
[+] Use is one-time, or is only occasional or spontaneous

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| + Work to be used contains limited new knowledge, content, or creative expression (in relation to previously copyrighted works) |

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**Describe the Amount of Your Intended Use in Relation to the Copyrighted Work as a Whole:**

| + Only limited and reasonable portions will be used |
| + The amount used falls within widely recognized fair use guidelines* vetted by key stakeholder groups [reference guidelines] |

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| + Use of the work has the potential to create or improve the market for the work |
| + The copy of the work to be used is a legal copy |

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The Average "Fairness Level," Based on Your Rating of Each of the 4 Factors, Is:

[see tool disclaimer for important clarifying information]:

Based on the information and justification I have provided above, I, David Berry, am asserting this use is FAIR under Section 107 of the U.S. Copyright Code.

Signature: David Berry
Date of Signature: 8/21/14

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Name: David Berry  
Job Title: Graduate Student  
Institution: Virginia Tech Department of Materials Science and Engineering  
Title of Work Used: Ageing and Failure Modes of IGBT Modules in High-Temperature Power Cycling  
Copyright Holder: V. Smet, F. Forest, J. J. Huselstein, F. Richardeau, Z. Khatir, S. Lefebvre, and M. Berkani  
Publication Status: Published  
Publisher: Industrial Electronics, IEEE Transactions on,  
Publication Year: 2011  
Description of Work: journal article  
Date of Evaluation: May 20, 2014  
Date of Intended Use: May 20, 2014

Describe the **Purpose** and Character of Your Intended Use:

[+] Use is one-time, or is only occasional or spontaneous  
[+] Use is for "criticism, comment, news reporting, teaching, (including multiple print copies for classroom use), scholarship or research"

Fair Use Evaluation Documentation

Compiled using the Fair Use Evaluator [cc] 2008 Michael Brewer & the Office for Information Technology Policy, http://librarycopyright.net/fairuse/
Describe the **Nature** of Your Intended Use of the Copyrighted Work:

[+] Work to be used has been previously PUBLISHED

Fair  Unfair

Describe the **Amount** of Your Intended Use in Relation to the Copyrighted Work as a Whole:

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[+] Proper attribution will be given with the intended use

Fair  Unfair
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[see tool disclaimer for important clarifying information]:

Fair     |     |     |     |     |     |     | Unfair
✓       |     |     |     |     |     |     |

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Fair Use Evaluation Documentation

Compiled using the Fair Use Evaluator [cc] 2008 Michael Brewer & the Office for Information Technology Policy, http://librarycopyright.net/fairuse/

Name: David Berry
Job Title: Graduate Student
Institution: Virginia Tech Department of Materials Science and Engineering
Title of Work Used: Electronic Components and Technology Conference (ECTC)
Copyright Holder: J. Sylvester.
Publication Status: N/A
Publisher: Electronic Components and Technology Conference (ECTC)
Place of Publication: Electronic Components and Technology Conference (ECTC)
Publication Year: 2012
Description of Work: journal article
Date of Evaluation: May 19, 2014
Date of Intended Use: May 19, 2014
Describe the **Nature** of Your Intended Use of the Copyrighted Work:

[+] Work to be used has been previously PUBLISHED

Fair [ ] [ ] [ ] [ ] [ ] [ ] [ ] Unfair

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Fair [ ] [ ] [ ] [ ] [ ] [ ] [ ] Unfair

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Fair [ ] [ ] [ ] [ ] [ ] [ ] [ ] Unfair
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Signature: **David Berry**
Date of Signature: **5/20/14**

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[+] Work to be used is primarily of a factual nature (non-fiction, collection of facts, etc.)

![Fair/Unfair Scale](image)

Describe the **Amount** of Your Intended Use in Relation to the Copyrighted Work as a Whole:

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![Fair/Unfair Scale](image)

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![Fair/Unfair Scale](image)
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[see tool disclaimer for important clarifying information]:

Fair  🔄  🔄  🔄  🔄  🔄  🔄  Unfair

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Signature:  David Berry
Date of Signature:  5/20/14

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Name: David Berry
Job Title: Graduate Student
Institution: Virginia Tech Department of Materials Science and Engineering
Title of Work Used: Reliable Integration of Double-Sided Cooled Stacked Power Switches based on 70 micrometer Thin IGBTs and Diodes
Copyright Holder: J. F. Li, A. Castellazzi, A. Solomon, and C. M. Johnson
Publication Status: Published
Publisher: Integrated Power Electronics Systems (CIPS), 2012 7th International Conference on, 2012
Publication Year: 2012
Description of Work: journal article
Date of Evaluation: May 19, 2014
Date of Intended Use: May 19, 2014

Describe the **Purpose** and Character of Your Intended Use:

[+] Use is transformative, i.e. it uses the existing work in a new way (creates an index to the work) or for a new purpose (parody, pastiche, instructional materials, etc.) Transformative works are favored because the purpose of U.S. Copyright Law is to encourage the development and dissemination of new knowledge to benefit the public and thereby advance learning.
Describe the **Nature** of Your Intended Use of the Copyrighted Work:

[+] Work to be used has been previously PUBLISHED

Fair [ ] [ ] [ ] [ ] [ ] [ ] [ ] Unfair [ ]

Describe the **Amount** of Your Intended Use in Relation to the Copyrighted Work as a Whole:

[+] Only limited and reasonable portions will be used

Fair [ ] [ ] [ ] [ ] [ ] [ ] [ ] Unfair [ ]

Describe the **Effect** of Your Intended Use on the Potential Market or Value of the Copyrighted Work:

[+] Proper attribution will be given with the intended use

Fair [ ] [ ] [ ] [ ] [ ] [ ] [ ] Unfair [ ]
The Average "Fairness Level," Based on Your Rating of Each of the 4 Factors, Is:

[see tool disclaimer for important clarifying information]:

Fair  |  |  |  |  |  |  | Unfair
✓     |  |  |  |  |  |  |   

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### Fair Use Evaluation Documentation

Compiled using the **Fair Use Evaluator** [cc] 2008 Michael Brewer & the Office for Information Technology Policy, [http://librarycopyright.net/fairuse/](http://librarycopyright.net/fairuse/)

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<th>David Berry</th>
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<td>Job Title</td>
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<tr>
<td>Institution</td>
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<td>Title of Work Used</td>
<td>New structure of power integrated module</td>
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<td>M. Mermet-Guyennet</td>
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<td>New structure of power integrated module</td>
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**Describe the **Purpose** and Character of Your Intended Use:**

- [+] Use is clearly defined and is restricted in scope (limited duration, not iterative, restricted access, etc.)
- [+] Use is one-time, or is only occasional or spontaneous

---

**Fair Use Evaluation Score:**

- [✓] Fair
- [ ] Neutral
- [ ] Unfair
Describe the **Nature** of Your Intended Use of the Copyrighted Work:

[+] Work to be used is primarily of a factual nature (non-fiction, collection of facts, etc.)
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Describe the **Amount** of Your Intended Use in Relation to the Copyrighted Work as a Whole:

[+] Only limited and reasonable portions will be used
[+] The amount used falls within widely recognized fair use guidelines\(^*\) vetted by key stakeholder groups [reference guidelines]

Describe the **Effect** of Your Intended Use on the Potential Market or Value of the Copyrighted Work:

[+] Use of the work has the potential to create or improve the market for the work
[+] The copy of the work to be used is a legal copy

\(^*\) Reference guidelines...
The Average "Fairness Level," Based on Your Rating of Each of the 4 Factors, Is:

[see tool disclaimer for important clarifying information]:

Fair Unfair

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Signature:  
Date of Signature: 8/21/14

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Name: David Berry  
Job Title: Graduate Student  
Institution: Virginia Tech Department of Materials Science and Engineering  
Title of Work Used: POWER MODULE PACKAGING WITH DOUBLE SIDED PLANAR INTERCONNECTION AND HEAT EXCHANGERS," 2013.  
Copyright Holder: Z. X. Liang, Martino, L., Ning, P., Wang, F  
Publication Status: Published  
Publisher: webpage patentdocs  
Place of Publication: http://www.faqs.org/patents/app/20130020694  
Publication Year: 2013  
Description of Work: patent application for new device  
Date of Evaluation: May 19, 2014  
Date of Intended Use: May 19, 2014

Describe the **Purpose** and Character of Your Intended Use:

[+] Use is transformative, i.e. it uses the existing work in a new way (creates an index to the work) or for a new purpose (parody, pastiche, instructional materials, etc.) Transformative works are favored because the purpose of U.S. Copyright Law is to encourage the development and dissemination of new knowledge to benefit the public and thereby advance learning.
Describe the **Nature** of Your Intended Use of the Copyrighted Work:

[+] Work to be used is primarily of a factual nature (non-fiction, collection of facts, etc.)

![Fair](true) ![Unfair](false)

Describe the **Amount** of Your Intended Use in Relation to the Copyrighted Work as a Whole:

[+] Only limited and reasonable portions will be used

![Fair](true) ![Unfair](false)

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![Fair](true) ![Unfair](false)
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[see tool disclaimer for important clarifying information]:

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Copyright Holder: Z. X. Liang, Martino, L., Ning, P., Wang, F
Publication Status: Published
Publisher: webpage patentdocs
Place of Publication: http://www.faqs.org/patents/app/20130020694
Publication Year: 2013
Description of Work: patent application for new device
Date of Evaluation: May 19, 2014
Date of Intended Use: May 19, 2014

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Fair | Unfair
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Signature: [Signature]
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Name: David Berry  
Job Title: Graduate Student  
Institution: Virginia Tech Department of Materials Science and Engineering  
Title of Work Used: Processing and Characterization of a 100% Low-Temperature Ag-Sintered Three-Dimensional Structure  
Copyright Holder: A. Masson, S. Azzopardi, F. Le Henaff, J. Y. Deletage, E. Woirgard, S. Bontemps, and J. Joguet  
Publication Status: Published  
Publisher: Power Electronics and Applications (EPE), 2013 15th European Conference on, 2013  
Place of Publication: Power Electronics and Applications (EPE), 2013 15th European Conference on, 2013  
Publication Year: 2013  
Description of Work: conference article  
Date of Evaluation: May 19, 2014  
Date of Intended Use: May 19, 2014

Describe the **Purpose** and Character of Your Intended Use:

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Rating Scale:  
- Fair  
- Unfair
Describe the **Nature** of Your Intended Use of the Copyrighted Work:

[+] Work to be used has been previously PUBLISHED

Fair Unfair

Describe the **Amount** of Your Intended Use in Relation to the Copyrighted Work as a Whole:

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Fair Unfair

Describe the **Effect** of Your Intended Use on the Potential Market or Value of the Copyrighted Work:

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Fair Unfair
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Fair ☑️ ☐ ☐ ☐ ☐ Unfair

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Name: David Berry
Job Title: Graduate Student
Institution: Virginia Tech Department of Materials Science and Engineering
Title of Work Used: Creep Behavior of Sintered Nanosilver Paste
Copyright Holder: Kewei Xiao
Publication Status: Unpublished
Publisher:
Place of Publication:
Publication Year:
Description of Work: research article-never published
Date of Evaluation: May 19, 2014
Date of Intended Use: May 19, 2014

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Fair Unfair

☑️ □ □ □ □ □ □
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</table>
The Average "Fairness Level," Based on Your Rating of Each of the 4 Factors, Is:

[see tool disclaimer for important clarifying information]:

<table>
<thead>
<tr>
<th>Fair</th>
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<th></th>
<th>Unfair</th>
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<tr>
<td>✓</td>
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</tbody>
</table>

Based on the information and justification I have provided above, I, David Berry, am asserting this use is **FAIR** under Section 107 of the U.S. Copyright Code.

Signature: ________________

Date of Signature: 5/20/14

*Disclaimer: This document is intended to help you collect, organize & archive the information you might need to support your fair use evaluation. It is not a source of legal advice or assistance. The results are only as good as the input you have provided by are intended to suggest next steps, and not to provide a final judgment. It is recommended that you share this evaluation with a copyright specialist before proceeding with your intended use.*
Name: David Berry
Job Title: Graduate Student
Institution: Virginia Polytechnic Institute and State University
Title of Work Used: Study of Robustness for Double-Sided Module with Rigid Substrates on Both Sides
Copyright Holder: J. Li, G. Q. Lu, and K. Ngo
Publication Status: N/A
Publisher: Center for Power Electronics
Place of Publication: Center for Power Electronics Annual Conference
Publication Year: 2012
Description of Work: Conference Paper
Date of Evaluation: August 21, 2014
Date of Intended Use: August 21, 2014

Describe the **Purpose** and Character of Your Intended Use:

[+] Use is clearly defined and is restricted in scope (limited duration, not iterative, restricted access, etc.)
[+] Use is one-time, or is only occasional or spontaneous
Describe the **Nature** of Your Intended Use of the Copyrighted Work:

[+] Work to be used is primarily of a factual nature (non-fiction, collection of facts, etc.)
[+] Work to be used contains limited new knowledge, content, or creative expression (in relation to previously copyrighted works)

Describe the **Amount** of Your Intended Use in Relation to the Copyrighted Work as a Whole:

[+] Only limited and reasonable portions will be used
[+] The amount used falls within widely recognized fair use guidelines* vetted by key stakeholder groups [reference guidelines]

Describe the **Effect** of Your Intended Use on the Potential Market or Value of the Copyrighted Work:

[+] Use of the work has the potential to create or improve the market for the work
[+] The copy of the work to be used is a legal copy
The Average "Fairness Level," Based on Your Rating of Each of the 4 Factors, Is:

[see tool disclaimer for important clarifying information]:

Fair [ ] [ ] [ ] [ ] [ ] [ ] Unfair

Based on the information and justification I have provided above, I, David Berry, am asserting this use is FAIR under Section 107 of the U.S. Copyright Code.

Signature:  
Date of Signature: 8/21/14

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Name: David Berry
Job Title: Graduate Student
Institution: Virginia Tech Department of Materials Science and Engineering
Title of Work Used: Image of product from webpage
Copyright Holder: Micross
Publication Status: Published
Publisher: Micross webpage
Place of Publication: webpage
Publication Year: unknown
Description of Work: picture of current state of art power modules
Date of Evaluation: May 19, 2014
Date of Intended Use: May 19, 2014

Describe the **Purpose** and Character of Your Intended Use:

[+] Use is for “criticism, comment, news reporting, teaching, (including multiple print copies for classroom use), scholarship or research”
[+] Use is one-time, or is only occasional or spontaneous
[+] Use is clearly defined and is restricted in scope (limited duration, not iterative, restricted access, etc.)

Fair Unfair

![Medium Fair](#)
Describe the **Nature** of Your Intended Use of the Copyrighted Work:

| (+) Work to be used has been previously PUBLISHED | (+) Work to be used contains limited new knowledge, content, or creative expression (in relation to previously copyrighted works) |

<table>
<thead>
<tr>
<th>Fair</th>
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<th></th>
<th></th>
<th>Unfair</th>
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</thead>
<tbody>
<tr>
<td>✔️</td>
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</tbody>
</table>

Describe the **Amount** of Your Intended Use in Relation to the Copyrighted Work as a Whole:

| (+) Only limited and reasonable portions will be used |

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Describe the **Effect** of Your Intended Use on the Potential Market or Value of the Copyrighted Work:

| (+) Proper attribution will be given with the intended use |

<table>
<thead>
<tr>
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[see tool disclaimer for important clarifying information]:

Based on the information and justification I have provided above, I, David Berry, am asserting this use is FAIR under Section 107 of the U.S. Copyright Code.

Signature: David Berry
Date of Signature: 5/20/14

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Name: David Berry
Job Title: Graduate Student
Institution: Virginia Tech Department of Materials Science and Engineering
Title of Work Used: IGBT Applications Handbook
Copyright Holder: On Semiconductor
Publication Status: Published
Publisher: On Semiconductor
Place of Publication: www.on-semi.com
Publication Year: 2012
Description of Work: handbook
Date of Evaluation: May 19, 2014
Date of Intended Use: May 19, 2014

Describe the **Purpose** and Character of Your Intended Use:

[+] Use is clearly defined and is restricted in scope (limited duration, not iterative, restricted access, etc.)
[+] Use is one-time, or is only occasional or spontaneous
Describe the **Nature** of Your Intended Use of the Copyrighted Work:

[+] Work to be used has been previously PUBLISHED

Fair [ ] [ ] [ ] [ ] [ ] [ ] [ ] Unfair [ ] [ ] [ ] [ ] [ ] [ ]

Describe the **Amount** of Your Intended Use in Relation to the Copyrighted Work as a Whole:

[+] Only limited and reasonable portions will be used

Fair [ ] [ ] [ ] [ ] [ ] [ ] [ ] Unfair [ ] [ ] [ ] [ ] [ ] [ ]

Describe the **Effect** of Your Intended Use on the Potential Market or Value of the Copyrighted Work:

[+] Proper attribution will be given with the intended use

Fair [ ] [ ] [ ] [ ] [ ] [ ] [ ] Unfair [ ] [ ] [ ] [ ] [ ] [ ]
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## Fair Use Evaluation Documentation

Compiled using the **Fair Use Evaluator** [cc] 2008 Michael Brewer & the Office for Information Technology Policy, [http://librarycopyright.net/fairuse/](http://librarycopyright.net/fairuse/)

<table>
<thead>
<tr>
<th>Name</th>
<th>David Berry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Job Title</td>
<td>Graduate Student</td>
</tr>
<tr>
<td>Institution</td>
<td>Virginia Tech Department of Materials Science and Engineering</td>
</tr>
<tr>
<td>Title of Work Used</td>
<td>JEDEC Standard JESD51-14</td>
</tr>
<tr>
<td>Copyright Holder</td>
<td>Joint Electron Device Engineering Council</td>
</tr>
<tr>
<td>Publication Status</td>
<td>Published</td>
</tr>
<tr>
<td>Publisher</td>
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<td>Place of Publication</td>
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<td>Description of Work</td>
<td>standard and documentation on its use</td>
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<td>Date of Evaluation</td>
<td>May 19, 2014</td>
</tr>
<tr>
<td>Date of Intended Use</td>
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</tbody>
</table>

### Purpose

Describe the **Purpose** and Character of Your Intended Use:

[-] Use is one-time, or is only occasional or spontaneous

[+] Use is for "criticism, comment, news reporting, teaching, (including multiple print copies for classroom use), scholarship or research"

<table>
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Describe the **Nature** of Your Intended Use of the Copyrighted Work:

- [+] Work to be used has been previously PUBLISHED
- [+] Work to be used is primarily of a factual nature (non-fiction, collection of facts, etc.)

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Describe the **Amount** of Your Intended Use in Relation to the Copyrighted Work as a Whole:

- [+] Only limited and reasonable portions will be used

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Based on the information and justification I have provided above, I, David Berry, am asserting this use is FAIR under Section 107 of the U.S. Copyright Code.

Signature: ____________________________
Date of Signature: ____________

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### Description of Work:
standard and documentation on its use

### Date of Evaluation:
May 19, 2014

### Date of Intended Use:
May 19, 2014

### Describe the **Purpose** and Character of Your Intended Use:

<table>
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[+] Only limited and reasonable portions will be used

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[+] Proper attribution will be given with the intended use
The Average "Fairness Level," Based on Your Rating of Each of the 4 Factors, Is:

[see tool disclaimer for important clarifying information]:

Fair | | | | | | Unfair

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Date of Signature: 5/20/14

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<td><strong>Institution:</strong></td>
<td>Virginia Tech Department of Materials Science and Engineering</td>
</tr>
<tr>
<td><strong>Title of Work Used:</strong></td>
<td>Applying Anand model to low-temperature sintered nanoscale silver paste chip attachment</td>
</tr>
<tr>
<td><strong>Copyright Holder:</strong></td>
<td>D.-j. Yu, X. Chen, G. Chen, G.-q. Lu, and Z.-q. Wang</td>
</tr>
<tr>
<td><strong>Publication Status:</strong></td>
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<td><strong>Date of Evaluation:</strong></td>
<td>May 19, 2014</td>
</tr>
<tr>
<td><strong>Date of Intended Use:</strong></td>
<td>May 19, 2014</td>
</tr>
</tbody>
</table>

Describe the **Purpose** and Character of Your Intended Use:

> [+] Use is socially beneficial (promotes the creation of new knowledge, learning, etc.) [define how]

![Fair Use Scale](image)
Describe the **Nature** of Your Intended Use of the Copyrighted Work:

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[+] Work to be used has been previously PUBLISHED

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[see tool disclaimer for important clarifying information]:

Fair [☐] [☐] [☐] [☐] [☐] [☐] [☐] Unfair

Based on the information and justification I have provided above, I, David Berry, am asserting this use is FAIR under Section 107 of the U.S. Copyright Code.

Signature:  

Date of Signature: 5/20/14

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Name: David Berry
Job Title: Graduate Student
Institution: Virginia Tech Department of Materials Science and Engineering
Title of Work Used: Transient Thermal Performance of IGBT Power Modules Attached by Low-Temperature Sintered Nanosilver
Copyright Holder: C. Gang, H. Dan, M. Yun-Hui, C. Xiao, W. Tao, C. Xu, and L. Guo-Quan
Publication Status: Published
Publisher: Device and Materials Reliability, IEEE Transactions on
Publication Year: 2012
Description of Work: journal article
Date of Evaluation: May 19, 2014
Date of Intended Use: May 19, 2014

Describe the Purpose and Character of Your Intended Use:

[+] Use is not-for-profit
[+] Use is one-time, or is only occasional or spontaneous

Fair Unfair
✔️ ❌ ❌ ❌ ❌ ❌ ❌ ❌

Page 1
Describe the **Nature** of Your Intended Use of the Copyrighted Work:

[+] Work to be used has been previously PUBLISHED

<table>
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</table>

Describe the **Effect** of Your Intended Use on the Potential Market or Value of the Copyrighted Work:

[+] The copy of the work to be used is a legal copy  
[+] Proper attribution will be given with the intended use

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