Chapter V Summary and Conclusions

Thermal and thermo-mechanical analysis using Finite Element Method (FEM) has been performed to evaluate an innovative three-dimensional power module packaged by a stacked-plate technique, namely, the MPIPPS (Metal Post Interconnected-Parallel Plate Structure), and the results are compared with that of a wire bond module.

Thermal modeling simulates and maps the temperature and heat flow distribution in both power modules during normal operation, taking into account effects of both size and location of the heat source as well as the heat spreader. Thermal modeling results show significantly lower junction temperatures in the MPIPPS module than in the wire bond module under the same single-side cooling conditions. The hottest spot (in IGBT chip) in the MPIPPS module has a temperature of 119 ^{o}C and is 17 ^{o}C lower than the hottest spot in the wire bond module. This is due to the fact that the MPIPPS module has a more uniform heat flow distribution. The presence of a top DBC substrate in MPIPPS module serves as a heat conduction path so that the excessive heat generated by high-power IGBT devices can be directed to the top DBC then flow back to lower temperature diode devices. The maximum junction temperature is further reduced in MPIPPS module by the implementation of double-side cooling, which can not be used in the wire bonding technique.

The subsequent thermo-mechanical modeling has evaluated the thermally induced responses of the power modules under two conditions. Both models are first subject to temperature cycling, in which the temperature in the structure changes uniformly between 0 and 125 ^{o}C. The models are also studied under power cycling condition, in which the temperature periodically changes from 0 ^{o}C to the power modules' working temperature. Temperature distribution obtained from thermal modeling is used in power cycling analysis. In both cycle conditions, the aluminum wire bonds in the wire bond module have shown plastic deformation over the regions where they attach to the device's emitter pads. However, the results have shown a more severe stress and strain situation around these weak locations during the temperature cycles than during the power cycling conditions. At the other end of the bonding wires, plastic deformation only occurs in temperature cycling conditions. This is because in power cycling condition, the temperature variation around the wire-substrate interfaces is much smaller than that in the device region. The wire bond shape distortion is also analytically predicted through FEM analysis. At the heating stage in temperature cycling, the wire bond bows more than it does in power cycling. In both cases the maximum displacement ranges about 10 microns at the center point of the wire bond. In the MPIPPS module, the solder joints that link the device to the top DBC exhibit significant plastic deformation and creep strain. Power cycling produces more plastic deformation at the solder joints between post and device due to more local heating and thus more severe high temperature creep of solder. Using a deformation-based thermal fatigue theory, the solder joints fatigue lives are predicted. In temperature cycling, the fatigue life around several solder joint locations is averaged to be about 20 cycles under the applied condition. In power cycling, solder joints between the top DBC and the copper posts have a fatigue life of about 200 cycles. However, the device-to-post solder joint fails within 10 cycles.

We conclude that the MPIPPS module is better in thermal management but is thermo-mechanically less reliable than the wire bond module.

Appendix A:
ABAQUS Input Files

I. MPIPPS, Power Cycling, Thermo-Mechanical Analysis Code:

```
*HEADING, SPARSE
*PREPRINT, ECHO=NO
**
**UNITS M, PA, SEC, CELSIUS
**
*SUPER DELETE, ID=Z111
*SUPER, ID=Z111, RECOVERY=NO
*RETAINED DOFS
RETAINED,
*NODE,NSET=NALL
     1,   7.26107E-10,   7.26107E-10,    -0.000889
......
  22130,      0.02208,     0.0313415,      0.001903
**
**  ELEMENT DEFINITIONS
**
*ELEMENT, TYPE=C3D8, ELSET=ALN
   1443,    1777,    1784,    2062,    2057,    1775,
1782,
   2061,    2056
......
*ELEMENT, TYPE=C3D8, ELSET=SUBCU
    463,    1779,    1786,    2064,    2059,    1777,
1784,
   2062,    2057
......
**   3445,    6481,    6478,    6645,    6648,    6480,
6477,
**   6644,    6647
......
*ELEMENT, TYPE=C3D8, ELSET=A27POST
   6385,     671,     674,     673,     672,   8924,   8921,
   8922,    8923
......
*ELEMENT, TYPE=C3D8, ELSET=SUPER-SL
    449,     842,     840,     834,     838,     674,     673,
    672,     671
......
*ELEMENT, TYPE=C3D8, ELSET=DVSLDG
      1,    1786,    1779,    2059,    2064,    1785,    1778,
   2058,    2063
......
*ELEMENT, TYPE=C3D8, ELSET=SI
**     225,    2063,    1785,    1778,    2058,    1787,
1783,
**    1776,    1780
    226,    1276,    1072,    1067,    1271,    1274,
1070,
   1065,    1269
......
**
*NSET,NSET=SBOTTOM
1776,1780,1783,1787,1778,1785,2058,2063
*NSET,NSET=STOP
6478,6481,6645,6648,6644,6647,6477,6480
*NSET,NSET=RETAINED
SBOTTOM,STOP,
**
**   ELEMENT PROPERTIES, LINEAR IN
SUPERMODEL
**
** ALN
**
*SOLID SECTION, ELSET=ALN,
MATERIAL=ALN
        1.,
**
** SUBCU
**
*SOLID SECTION, ELSET=SUBCU,
MATERIAL=CU
        1.,
**
** 27POST
**
*SOLID SECTION, ELSET=A27POST,
MATERIAL=CU
        1.,
**
** SUPER-SLDG
**
*SOLID SECTION, ELSET=SUPER-SL,
MATERIAL=SOLDER
        1.,
**
** DVSLDG
**
*SOLID SECTION, ELSET=DVSLDG,
MATERIAL=SOLDER
        1.,
**
** SI
**
*SOLID SECTION, ELSET=SI, MATERIAL=SI
        1.,
**
** EUTECTIC SOLDER (63SN/37PB)
**
*MATERIAL,NAME=SOLDER
*ELASTIC, TYPE=ISO
   2.64E+10,       0.36,       0.
   1.25E+10,      0.365,       50.
     6.9E+9,      0.378,       100.
**
*EXPANSION, TYPE=ISO
    2.38E-5,       0.
    2.94E-5,       50.
    2.98E-5,       100.
**
*PLASTIC
    3.64E+7,         0.,       0.
```

```
    1.25E+8,          0.5986,    0.
    1.52E+7,          0.,        50.
    1.0382E+8,        0.598784,  50.
     9.6E+6,          0.,        100.
    9.819E+7,         0.59861,   100.
**
** ALN
**
*MATERIAL, NAME=ALN
**
**
*ELASTIC, TYPE=ISO
    3.3E+11,        0.23
**
*EXPANSION, TYPE=ISO, ZERO=0.
     4.5E-6,
**
** CU
**
*MATERIAL, NAME=CU
**
**
*ELASTIC, TYPE=ISO
   1.35E+11,        0.34
*PLASTIC, HARDENING=KINEMATIC
1.379E+8,0.0
2.715E+8,0.098982
**
*EXPANSION, TYPE=ISO, ZERO=0.
     1.7E-5,
**
** SI
**
*MATERIAL, NAME=SI
**
**
*ELASTIC, TYPE=ISO
    1.3E+11,        0.28
**
*EXPANSION, TYPE=ISO, ZERO=0.
     4.1E-6,
**
*INITIAL CONDITIONS,TYPE=TEMPERATURE
NALL,0.0
** THE CELSIUS TEMPERATURE SCALE WAS
CHOSEN INSIDE THE SUPERELEMENT SO
** THAT WHEN THE *SLOAD CASES, HOT AND
COLD ARE CALLED OUT AT THE
** GLOBAL LEVEL, SCALE FACTORS OF 1.0
AND 0.0 (RESPECTIVELY) PROVIDE A
** DELTA-T OF 125 DEGREES. IF KELVIN WERE
USED, THE SCALE FACTORS WOULD
** BE .3141 AND 0.0.
*SLOAD CASE,ID=HOT
*TEMPERATURE
 1,    32.732
 2,    32.786
......
 21015,    76.038
** 21017,    114.129
** 21018,    113.026
** 21019,    111.923
** 21020,    110.821
** 21022,    114.23
** 21023,    113.158
** 21024,    112.086
** 21025,    111.013
** 21026,    109.941
** 21027,    108.869
** 21028,    113.229
** 21029,    112.187
** 21030,    111.145
** 21031,    110.104
** 21032,    109.062
** 21033,    108.02
** 21034,    112.228
** 21035,    111.217
** 21036,    110.205
** 21037,    109.194
** 21038,    108.182
** 21039,    107.171
** 21040,    111.227
** 21041,    110.246
** 21042,    109.265
** 21043,    108.284
** 21044,    107.303
** 21045,    106.322
** 21047,    109.275
** 21048,    108.325
** 21049,    107.374
** 21050,    106.423
** 22097,    94.378
** 22098,    94.214
** 22099,    94.05
** 22100,    93.885
** 22102,    94.41
** 22103,    94.25
** 22104,    94.091
** 22105,    93.931
** 22106,    93.771
** 22107,    93.612
** 22108,    94.277
** 22109,    94.122
** 22110,    93.967
** 22111,    93.813
** 22112,    93.658
** 22113,    93.503
** 22114,    94.144
** 22115,    93.994
** 22116,    93.844
** 22117,    93.694
** 22118,    93.544
** 22119,    93.394
** 22120,    94.011
** 22121,    93.866
** 22122,    93.721
** 22123,    93.576
** 22124,    93.43
** 22125,    93.285
** 22127,    93.738
** 22128,    93.598
** 22129,    93.457
** 22130,    93.317
*SLOAD CASE,ID=COLD
```

```
*TEMPERATURE
NALL,0.0
**
*NSET,NSET=NPIN
10001,
*NSET,NSET=NZZ
10364,10450
**
*SLOAD CASE,ID=PIN
*BOUNDARY
NPIN,ENCASTRE
*SLOAD CASE,ID=ZZ
*BOUNDARY
NZZ, 3,3
*END SUPER
**
**
** USAGE LEVEL MODEL DEFINITION
**
** UNITS M, PA, SEC, KELVIN
**
*NODE,NSET=NALL
     1,   7.26107E-10,   7.26107E-10,     -0.000889
......

  22130,      0.02208,     0.0313415,      0.001903
*ELEMENT, TYPE=C3D8, ELSET=FINEPOST
   6569,   21160,   21161,   21167,   21166,   21196,
21197,
  21203,   21202
......
*ELEMENT, TYPE=C3D8, ELSET=FINESLDG
   6469,    1783,   21017,   21023,   21022,   21052,
21053,
  21059,   21058
......
**
** ELEMENTS 3445 CU, AND 225 SI,
**
*ELEMENT, TYPE=C3D8, ELSET=SUBCU
3445, 6481, 6478, 6645, 6648, 6480, 6477, 6644, 6647
*ELEMENT, TYPE=C3D8, ELSET=SI
225, 2063, 1785, 1778, 2058, 1787, 1783, 1776, 1780
***
*** THIS IS TO DEFINE "RETAINED" NSET
AGAIN IN USAGE MODEL PART
***
*NSET,NSET=SBOTTOM
1776,1780,1783,1787,1778,1785,2058,2063
*NSET,NSET=STOP
6478,6481,6645,6648,6644,6647,6477,6480
*NSET,NSET=RETAINED
SBOTTOM,STOP,
**
** PHYSICAL CONSTANTS
**
*PHYSICAL CONSTANTS, ABSOLUTE ZERO=0.
**   THIS IS NEEDED FOR CREEP.
**
** SUBCU
**
*SOLID SECTION, ELSET=SUBCU,
MATERIAL=CU
        1.,
**
** SI
**
*SOLID SECTION, ELSET=SI, MATERIAL=SI
        1.,
**
** FINEPOST
**
*SOLID SECTION, ELSET=FINEPOST,
MATERIAL=CU
        1.,
**
** FINESLDG
**
*SOLID SECTION, ELSET=FINESLDG,
MATERIAL=SOLDER
        1.,
**
** EUTECTIC SOLDER (63SN/37PB)
**
*MATERIAL,NAME=SOLDER
*ELASTIC, TYPE=ISO
   2.64E+10,       0.36,       273.
   1.25E+10,      0.365,       323.
     6.9E+9,      0.378,       373.
**
*EXPANSION, TYPE=ISO
    2.38E-5,       273.
    2.94E-5,       323.
    2.98E-5,       373.
**
*PLASTIC
    3.64E+7,         0.,       273.
    1.25E+8,         0.5986,    273.
    1.52E+7,         0.,       323.
    1.0382E+8,       0.598784,  323.
     9.6E+6,         0.,       373.
    9.819E+7,        0.59861,   373.
*CREEP, LAW=HYPERB
** FOR US UNIT     12423.,     8.69E-4,       1.89,
61417.,      8.314
    12423.,     1.26E-7,        1.89,      61417.,      8.314
**
** CU
**
*MATERIAL, NAME=CU
**
*DENSITY
      8930.,
**
*ELASTIC, TYPE=ISO
   1.35E+11,       0.34
**
*EXPANSION, TYPE=ISO, ZERO=273
     1.7E-5,
**
*PLASTIC, HARDENING=KINEMATIC
1.379E+8,0.0
2.715E+8,0.098982
```

```
**
*CONDUCTIVITY, TYPE=ISO
       393.,
**
*SPECIFIC HEAT
       383.,
**
** SI
**
*MATERIAL, NAME=SI
**
*DENSITY
      2330.,
**
*ELASTIC, TYPE=ISO
   1.3E+11,       0.28
**
*EXPANSION, TYPE=ISO, ZERO=273
     4.1E-6,
**
*CONDUCTIVITY, TYPE=ISO
       136.,
**
*SPECIFIC HEAT
       703.,
*INITIAL CONDITIONS, TYPE=TEMPERATURE
NALL,273.0
**
** SUPERELEMENT USAGE
**
** THE FOLLOWING ARE THE NODES AROUND
3445(CU) AND 225(SI)
**  THESE NODES HAS BEEN DEFINED AS
"SUPER ELEMENTS" #1!
** NOTE: ABOUT THE USE OF COMMA SEE PP.
8.3.2-2, ABA/STD V.2
**    THESE ELEMENTS ARE IN SUPER MODEL,
TYPE=Z111
**
*ELEMENT,TYPE=Z111,ELSET=TWOENDS
1,1776,1780,1783,1787,1778,1785,2058,2063,6478,64
81,
6645,6648,6644,6647,6477,6480
**
**  NOTE: ELEMENT 3445 AND 225 IS WHERE
THE CONTACT SURFACE
**        IS, SO MUST NOT BE DEFINED IN SUPER
MODEL IN
**        ABAQUS V5.8, NEED TO BLOCK THEM
USING ** IN SUPER MODEL
**
*SUPER PROPERTY,ELSET=TWOENDS,
POSITION TOL=1.0E-7
**
*ELSET,ELSET=STDBC
3445,
*ELSET,ELSET=SDIE
225,
*NSET,NSET=NSLDG1,GEN
22097,22100,1
22102,22125,1
22127,22130,1
*NSET,NSET=NSLDG2,GEN
21017,21020,1
21022,21045,1
21047,21050,1
**
**    SURFACES
**
*SURFACE DEFINITION,NAME=STDBC
STDBC,S1
*SURFACE DEFINITION,NAME=SDIE
SDIE,S2
*CONTACT NODE SET,NAME=NSLDG1
NSLDG1,
*CONTACT NODE SET,NAME=NSLDG2
NSLDG2,
*CONTACT
PAIR,TIED,ADJUST=.001,INTERACTION=TIED,S
MALL SLIDING
NSLDG1,STDBC
NSLDG2,SDIE
*SURFACE INTERACTION,NAME=TIED
**
** STEP DEFINITION
**
********************************************
** 3 CYCLES MODELED - RAMP TO 125
C,HOLD, RAMP TO 0,HOLD
********************************************
**
*STEP,INC=500,NLGEOM,AMP=RAMP
*VISCO,CETOL=1.E-3
1,60., 1.E-7
**THE .001, 10., 1.E-7 SETUP, ONLY 36
INCREMENTS
*RESTART,WRITE,FREQ=3
***TEMPERATURE
**NALL, 398.0
*TEMPERATURE, OP=NEW
   1776,     382.718
   1780,     378.472
......
*SLOAD, OP=NEW
TWOENDS,HOT,1.0
TWOENDS,ZZ,0.0
TWOENDS,PIN,0.0
**
*FILE FORMAT, ASCII
*NODE PRINT, FREQ=999
U,
*NODE FILE, FREQ=999
U,
**
*EL PRINT, POS=INTEG, FREQ=999
S,
E,
*EL FILE,  POS=INTEG, FREQ=999
S,
E,
*ENERGY FILE,FREQ=99
*END STEP
*****************************
** STEP 2: CREEP 900 SEC.
```

```
**
*STEP,INC=500,NLGEOM
*VISCO, CETOL=1E-3
1.0, 900., 1.E-7, 75.
*RESTART,WRITE,FREQ=5
*END STEP
*****************************
** STEP 3: RAMP TO 0 DEG. C
**
*STEP,INC=500,NLGEOM,AMP=RAMP
*VISCO,CETOL=1.E-3
1,60., 1.E-7
*RESTART,WRITE,FREQ=3
*TEMPERATURE
NALL, 273.0
*SLOAD, OP=NEW
TWOENDS,COLD,1.0
TWOENDS,ZZ,0.0
TWOENDS,PIN,0.0
*END STEP
*****************************
** STEP 4: CREEP 900 SEC.
**
*STEP,INC=500,NLGEOM
*VISCO, CETOL=1E-3
1.0, 900., 1.E-7, 75.
*RESTART,WRITE,FREQ=5
*END STEP
*****************************
** STEP 5 HEATING
*STEP,INC=500,NLGEOM,AMP=RAMP
*VISCO,CETOL=1.E-3
1,60., 1.E-7
*RESTART,WRITE,FREQ=3
***TEMPERATURE
**NALL, 398.0
*TEMPERATURE, OP=NEW
   1776,     382.718
......
*SLOAD, OP=NEW
TWOENDS,HOT,1.0
TWOENDS,ZZ,0.0
TWOENDS,PIN,0.0
*END STEP
*****************************
** STEP 6: CREEP 900 SEC.
**
*STEP,INC=500,NLGEOM
*VISCO, CETOL=1E-3
1.0, 900., 1.E-7, 75.
*RESTART,WRITE,FREQ=5
*END STEP
*****************************
** STEP 7: RAMP TO 0 DEG. C
**
*STEP,INC=500,NLGEOM,AMP=RAMP
*VISCO,CETOL=1.E-3
1,60., 1.E-7
*RESTART,WRITE,FREQ=3
*TEMPERATURE
NALL, 273.0
*SLOAD, OP=NEW
TWOENDS,COLD,1.0
TWOENDS,ZZ,0.0
TWOENDS,PIN,0.0
*END STEP
*****************************
** STEP 8: CREEP 900 SEC.
**
*STEP,INC=500,NLGEOM
*VISCO, CETOL=1E-3
1.0, 900., 1.E-7, 75.
*RESTART,WRITE,FREQ=5
*END STEP
*****************************
** STEP 9 HEATING
*STEP,INC=500,NLGEOM,AMP=RAMP
*VISCO,CETOL=1.E-3
1,60., 1.E-7
*RESTART,WRITE,FREQ=3
***TEMPERATURE
**NALL, 398.0
*TEMPERATURE, OP=NEW
   1776,     382.718
......
*SLOAD, OP=NEW
TWOENDS,HOT,1.0
TWOENDS,ZZ,0.0
TWOENDS,PIN,0.0
*END STEP
******************************
** STEP 10: CREEP 900 SEC.
**
*STEP,INC=500,NLGEOM
*VISCO, CETOL=1E-3
1.0, 900., 1.E-7, 75.
*RESTART,WRITE,FREQ=5
*END STEP
******************************
** STEP 11: RAMP TO 0 DEG. C
**
*STEP,INC=500,NLGEOM,AMP=RAMP
*VISCO,CETOL=1.E-3
1,60., 1.E-7
*RESTART,WRITE,FREQ=3
*TEMPERATURE
NALL, 273.0
*SLOAD, OP=NEW
TWOENDS,COLD,1.0
TWOENDS,ZZ,0.0
TWOENDS,PIN,0.0
*END STEP
******************************
** STEP 12: CREEP 900 SEC.
**
*STEP,INC=500,NLGEOM
*VISCO, CETOL=1E-3
1.0, 900., 1.E-7, 75.
*RESTART,WRITE,FREQ=5
*END STEP
```

II. Other Input Files

These input files include: thermal analysis input files for both models; the wire bond model thermal-structural input files (temperature cycling and power cycling); and the MPIPPS model thermal-structural input file (temperature cycling). Due to the page limit, not all of these files are attached to the thesis.

Appendix B:
Animations

Vita

Sihua Wen (Simon) was born on January 11, 1975 in Xinjiang, China, to Mrs. Shuying Sun and Mr. Jingming Si. He received his elementary, secondary and high school education in the school, where his parents taught for 18 years in the district of Weinan, Shaanxi, a small city close to the origin of the silk road. After five wonderful, unforgettable years at Tsinghua University in Beijing, he received his B.S. degree in Materials Science & Engineering on June 30, 1997. The author hopes to pursue a doctorate in Materials Science & Engineering at Virginia Tech in the future.