Semiconductor Devices and Their Use in Power Electronic Applications

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Abstract: - Power semiconductor devices are the key electronic components used in power electronic systems. The solid-state power electronic revolution started with the invention of the thyristor or Silicon Controlled Rectifier (SCR) in 1956, and many power semiconductor devices have been produced since then. Advances in semiconductor technology have improved the efficiency of electronic devices which resulted in reduced cost, weight and size of power electronic systems. Power Integrated Circuits (PIC) have been developed as a result of recent advances in integration technology, which led to a significant improvement in reliability of power modules. This has extended the use of power converters for portable, aerospace and automotive applications. Thyristors and Insulated Gate Bipolar Transistors (IGBT's) have been used extensively in power electronic circuits. Power diodes are some of the important devices for inverter and freewheeling applications. Diode reverse recovery under high di/dt operating conditions may result device and circuit failure.
In this paper, detailed study and progress made in power semiconductor devices, their characteristics, packaging, thermal issues and different high power application are givens.

Key-Words: - Power Semiconductors Devices, Thermal Effects, Device Packaging, Power Applications.

1 Introduction

Power level requirements and switching frequency are continually increasing in the power electronic industry. This demands larger discrete devices and larger multi chip modules or series / parallel combination of these, with faster switching speed. Today, MOSFETs, IGBTs and Thyristors are the main devices used in many applications including power conversion and motor drives. MOSFETs are unipolar devices which means that they can be switched faster than bipolar devices, but their power ratings are much lower.

. Due to their widespread use in industry and the inherently high operating stress conditions, assessment of their failure mechanisms and reliability is a key issue.

Power semiconductor packaging is complicated by several factors. These include:

- Large currents that flow into and out of the silicon chips and package,
- The high voltages between terminals,
- The amount of power which is dissipated as heat and
- The large temperature excursions that devices and packages can undergo during operation.

The reliability of any electronic package depends to a large extent on its construction. Electronic packages for discrete devices and power modules are composed of multilayer, dissimilar materials, which are joined together by different methods including solder and adhesive. The difference in the coefficient of thermal expansion (CTE) causes these materials to expand and contract at different rates on heating and cooling. This is the main cause for the bond thermal stresses observed after die attachment in surface mounted devices, as well as for thermal fatigue observed in intermediate soldered joints between the insulating substrate and the base plate in conventional power modules. Therefore, a key consideration in the packaging of devices is that bonds between different materials are able to sustain the mechanical and thermal stresses over its service life. Otherwise it fractures prematurely, terminating the functionality of the whole package.

In designing multi chip power modules, one must consider few critical issues such as package parasitic inductance and current sharing between chips within the module. Parasitic inductance is an immediate concern since it can have a significant influence on the switching losses due to voltage overshoot. Another area of concern is the uneven distribution of current between parallel chips within the modules and between parallel-connected power modules.

Conventionally, high power electronic packages are of a stack configuration with several silicon chips connected in parallel. The chips are soldered onto insulating substrates made of typically heat conductive ceramic (usually aluminium oxide Al2O3 or aluminium nitride ALN). These are sandwiched between two thin copper layers, and the entire assembly of the die and the direct copper bonded (DCB) is soldered to a copper base plate. Some surface mounted technologies use a thermally conductive epoxy to attach semiconductor die directly onto the lead frame. Typical example of this technology is the Smartpack module [1]. The entire structure is overmoulded in an epoxy resin (moulded encapsulation) that forms the package itself and provide the electrical insulation needed, thus avoiding the use of intermediate substrates. Recently, direct mounting on metallised Ceramic heat-sink has been proposed for low power semiconductor devices (CeramTec).

Any electronic package undergoes three types of thermal loading during its lifetime:

- Processing: Problems arising during processing may include some defects in the silicon chips themselves.
- Testing: Every product undergoes testing.
- Operation in the field: Service environment may include thermal cycling.

The block diagram in figure 1a shows a summary of the main sources of failures. Details of these failure types are given in the following section.

2 Failure Mechanisms

2.1 Failure mechanisms relating to the silicon chip
2.2 Oxide defects
2.3 Ion migration
2.4 Current crowding / filamentation
2.5 Back metal delamination
2.6 External impacts
2.7 Operating conditions
2.8 Operating frequency
2.9 Short circuit conditions
2.10 The encapsulation
    2.10.1 Cracking of wire bond
    2.10.2 Partial discharge and insulation failure
    2.10.3 Delamination
    2.10.4 Solder fatigue

3 Current sharing

3.1 Static current sharing (figures 2 and 3).
3.2 Dynamic Behaviour (figures 4 and 5).
3.3 External circuit influence on sharing (fig.7).
3.4 Temperature de-rating

4 Semiconductor Devices for Thermal Stress Relief

Electrical circuit breakers were developed to protect circuits against faults. They are required to control electrical power networks by switching circuits ON, carrying load currents and switching circuits OFF, to isolate them with manual or automatic operation.

Conventional circuit breakers (CCBs) have been used for a long time for interruption of fault currents. Because of the thermal and electrical stresses inherent in opening and closing of conventional circuit breakers, such breakers have traditionally been very large and expensive devices, requiring expensive maintenance after a number of switching operations. Arcing which occurs across the contacts during interruption of fault current can damage contact electrodes and restricting nozzles [2]. For this reason conventional circuit breakers require frequent inspection and expensive maintenance. The problem of arcing becomes very acute for breaker applications where high switching frequency is required such as conveyor drives, industrial heaters, test beds etc.

In the last few decades a great progress has been achieved in the performance characteristics of conventional circuit breakers (CCBs) in respect of their voltage ratings, breaking capacities and speed of operation. In spite of that, the basic principle of conventional electromechanical circuit breaker technology has changed very little in more than 50 years. The main reason for its continuing popularity is its good reliability.

4.1 There are three basic requirements that a circuit breaker must meet:

1) It must conduct service load currents with minimal power loss.

2) It should be capable of fast transition to its blocking state without damaging itself in the process.

3) It must block any current from flowing when it is open, despite the high voltage across its terminals.

The conventional mechanical circuit breaker gives excellent results for the first and third of these requirements, but it could fail in the second due to transient conditions of the switching circuits.

4.2 Types of Traditional Circuit Breakers

1) Air-Break Circuit Breaker (CB).
2) Air-Blast CB.
3) Sulphur Hexafluride (SF_6) CB.
4) Oil CB.
5) Vacuum CB.

Looking at the various types of circuit breakers, the problems of arcing and maintenance immediately spring to mind. Also the size, cost and reliability are other important factors that need looking into. Engineers have speculated for many years about the possibility of replacing the existing conventional circuit breaker designs with new designs using semiconductor devices.

5 Solid-State Circuit Breakers

Over the last few years, power semiconductor devices have evolved to a point where a single device can carry few thousands of Amps and can block few thousands of Volts. The feasibility of using semiconductor devices for circuit breaker applications was examined by many workers [3, 4, 5].

Semiconductors switching devices have many advantages which include fast switching operation (High frequency applications) and low maintenance. Due to the absence of moving parts there is no arcing, contact bounce or erosion. Recently, considerable progress has been made in the development of low power solid-state breakers for AC and DC applications [3, 4, 5]. The main disadvantage of the solid-state breaker is the high thermal losses generated by the continuous load current.

Electronic switching devices, such as thyristors and GTO's, always have some voltage drop across their terminals resulting in heating through the I^2R Loss. At very high currents, the electromechanical breaker remains firmly established, with no short-term likelihood that the solid-state breaker replacing it. A hybrid form of switch has emerged (ref. 6) which marries the advantages of both ; see Figures (8) and (9).

6 Hybrid Circuit Breaker

The continuous current is handled by the conventional breaker, whereas the make and break processes are handled by power semiconductor devices (thyristors) connected in parallel with the breaker contacts. When switching on, the thyristors are fired first, these carry the inrush current and prevent arcing. As soon as the main contacts close, the contact resistance is lower than the resistance of the semiconductors, and consequently the current will commutate to the contact path. The continuous current is now carried by the breaker with negligible losses.

On disconnection, the thyristors are fired and the current will again pass through the thyristors because the resistance of this current path is lower that the resistance of the arc path. Again the arc will almost be eliminated and the thyristors will eventually block the voltage.

A single-phase hybrid model circuit breaker has been demonstrated using thyristors [6].
Similar work with using Insulated Gate Bipolar Transistors (IGBTs) instead of thyristors in the Hybrid Circuit Breaker (HCB) has been done and results are presented in figures (10 and 11). The main power handling limitations here are the maximum current and voltage ratings of the devices in parallel with the conventional breaker.
Figures (8 and 9) shows the HCB circuit layout and block diagram of the whole system. Figure 10 shows the CB feeding resistive load without the parallel IGBT, and the effect of arcing is clearly evident on the voltage waveform. Figure 11 shows the corresponding case with IGBT in parallel with CB. It can be clearly seen that the arc has been eliminated and no noise present on the voltage waveform.

7 High Power Hybrid Circuit Breaker

For these applications, devices need to be connected in series (for high voltage) and in parallel (for high current). In series operation of power semiconductor devices the important issue is to maintain equal blocking voltage sharing among devices in the series string during the steady state as well as during the transient state. Since

voltage unbalance is due to device parameter spread and gate drive delays, careful selection of devices which has low parameter spread and synchronising gate drive signals will minimise the problems associated with series connection. In practical situations this is rather impossible and therefore different mitigation techniques have been developed for different power devices.
Successful paralleling of devices requires care and adequate de-rating due to variations in device characterics and layout as discussed before.

Further details of problems encountered in series and parallel applications are given in reference [7] and [8] respectively.

8 Thermoelectric cooling using Semiconductor Devices

The growing thermal management problem in microelectronics industry due to the continuing push for higher packing densities of semiconductor devices in Giant Scale Integrated Circuits (GSI) has forced designers to search for new cooling methods.

The concept of thermal management in microelectronics circuits is changing, and the potential for solid-state cooling to solve heating problems is emerging. In the past many electrical and electronic circuits are cooled by forced air produced by electric fans. These are usually bulky, noisy, inefficient, and could be the source of failures in electronic circuits due to imported dust and other particles into the system which cause short circuits.

Recent advances in thermoelectric Peltier devices and associated capabilities to shrink thermoelectric modules enabled new solutions for microelectronic circuits cooling [9]. Two approaches for implementation for thermoelectric cooling are possible:

- Targeted (Hotspot) cooling; in this option, only the hottest spots on the silicon chip is cooled (Sometimes well below ambient temperatures to increase clock speed). The coefficient of performance is not critical because small fraction of total chip power is handled.
- Management of entire chip load - thermoelectrically enhanced heat sink. In this case the energy efficiency (Coefficient of Performance – COP) is of paramount importance and industry is not receptive to designs that greatly increase the total heat load that must be dissipated by the heat sink.

9 Conclusion

An overview of thermal issues and, failure mechanisms in power semiconductor devices are presented. Failures related to silicon chip, package structure, operating conditions and other external factors are discussed. The role of power semiconductor devices in thermal management is explored. The main advantage of using power semiconductor devices in circuit breaker applications is that the effect of arcing could be eliminated completely. This leads to major improvements which include:

- Reduction of size and weight,
- Reduction of pollution,
- Improved speed of operation and
- Improved efficiency

Peltier semiconductor devices can be used in many other applications for both heating and cooling systems.

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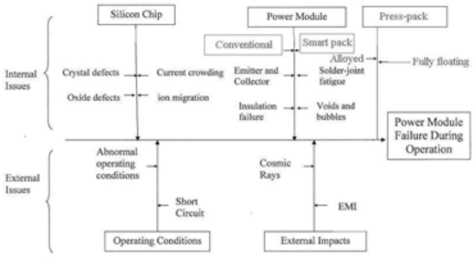

Fig. 1a: Potential Failure in Power Modules and Discrete Devices

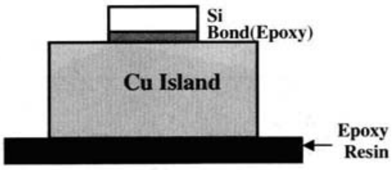

Fig. 1b: Simplified model of a SmartPack

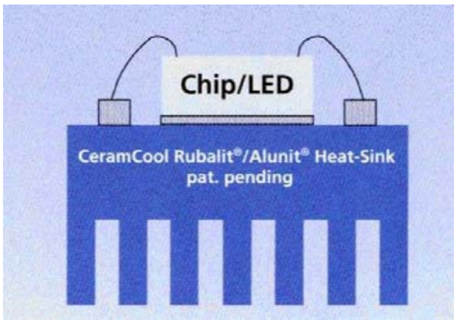

Fig. 1c: Ceramic Heat-Sink

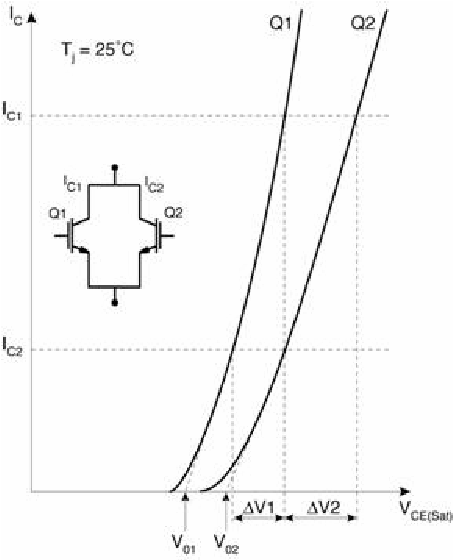

Fig. 2: IGBT module output characteristics

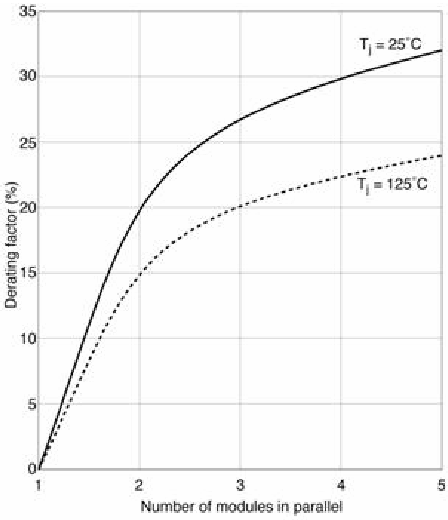

Fig. 3: Static de-rating factor vs number of DIM800DDM17-A000 IGBT modules in parallel

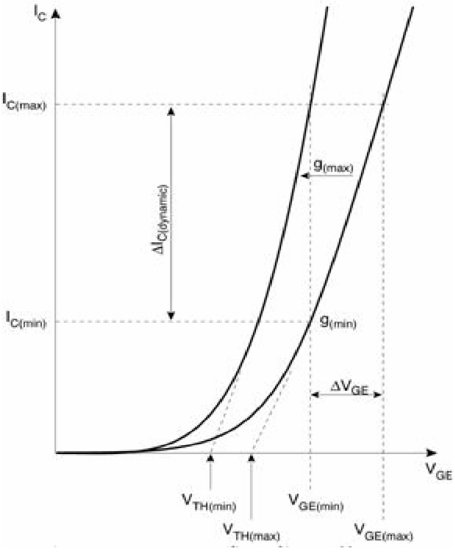

Fig. 4: IGBT module transfer characteristics

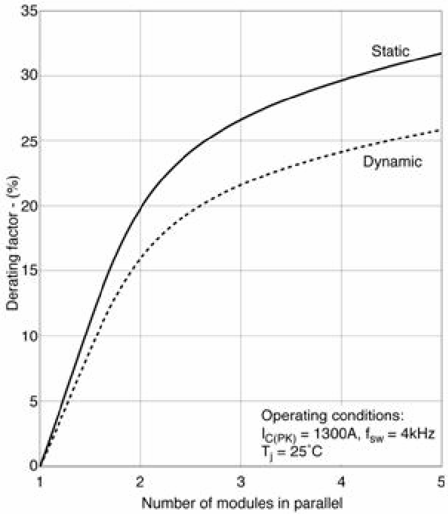

Fig. 5: Comparison of static and dynamic factors for DIM800DDM17-A000

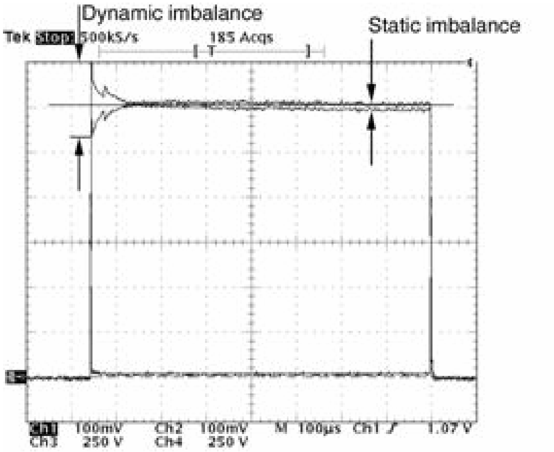

Fig. 6: Static and dynamic collector current de-rating imbalance for two DIM800DDM17-A000 modules in parallel. Vertical scale 100A/div Horizontal scale 100us/div

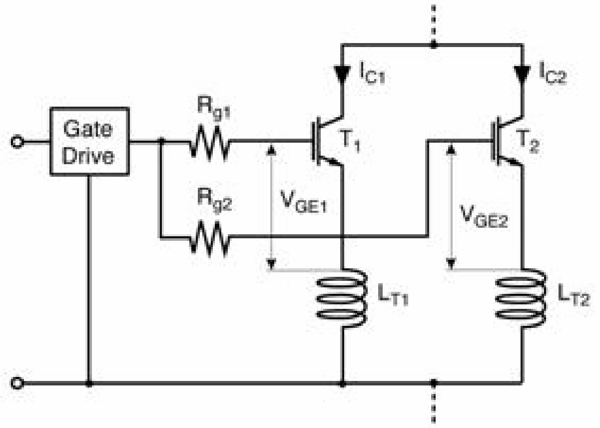

Fig. 7: Use of R_{g1} and R_{g2} to restore dynamic balance

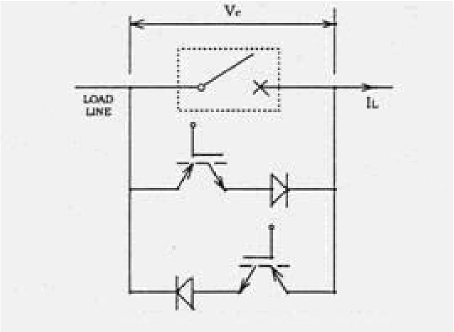

Fig. 8: Hybrid Circuit Breaker Configuration

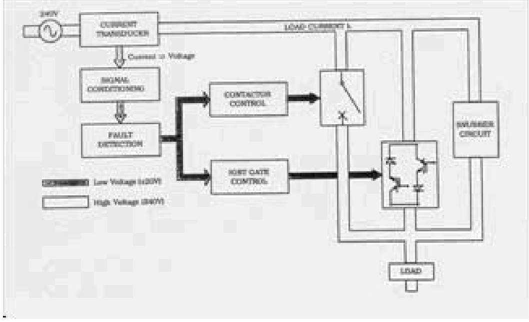

Fig. 9: Hybrid Circuit Breaker Configuration

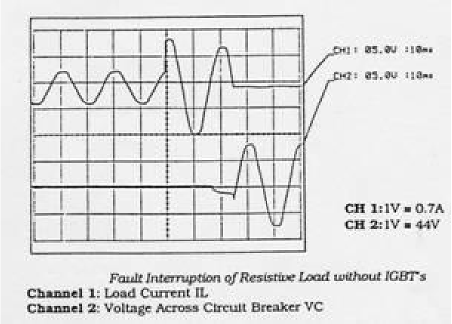

Fig. 10: Fault Interruption of Resistive load without IGBTs

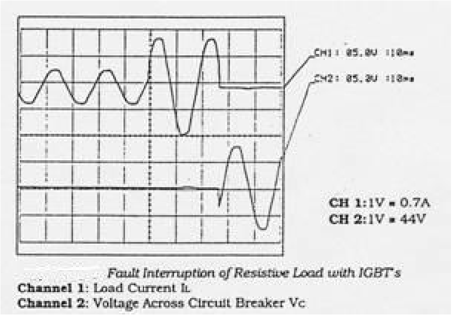

Fig. 11 Fault Interruption of Resistive load with IGBTs