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RESEARCH ARTICLE

POWER DEVICES FOR AUTOMOTIVE ELECTRICAL SYSTEMS: COMPARATIVE STUDY

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ABSTRACT

Continued electrification of traditionally mechanical loads, such as, power assist steering, etc. As well as the introduction of new loads, like seat heating, electric air conditions and AC power points will overburden the traditional 14 Volt power generation and distribution system. With this growing of electrical power demand in modern vehicles, a higher voltage electrical system becomes mandatory. The vehicle industry is currently pursuing a 42 volt system that selected by industry-wide research consortiums as a new standard. Although the switching to the 42 volt system will revolutionize the automotive industry but this switching can not be easily achieved in a short period due to the huge industrial infrastructure of the traditional 14 volt system. It became mandatory to study the power semiconductor switching devices that constitute the heart of modern vehicle electronics systems. However, In this paper, theoretical and practical comparative study of three semiconductor switching devices are demonstrated. The performance of these devices have been analyzed and compared from the view point of power electronics. Moreover, for completeness, a brief review of other power devices have been incorporated.

INTRODUCTION

Power electronics is enabling technology for the development of the environmentally friendly and fuel efficient vehicles. This power electronics is often said to have brought in the second electronics revolution. The first electronics revolution made modern microelectronics available. Advancements in power semiconductor technologies have made it feasible to develop new, high power automotive electronic systems and low emission vehicles. The power semiconductor device is the heart of modern electronics systems. The majority of these power semiconductor devices are used for motor drives, electronic ignition systems and converters. These devices have a major rule in drive by wire applications including brake by wire, steer by wire etc. Power semiconductors typically represent a major cost contributor in many modern automotive power electronics systems. Power electronics engineers have always dreamed of using ideal switching device especially in automotive

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applications. Such device should has large voltage and current ratings, zero conduction drop, zero leakage current in blocking condition, high temperature and radiation withstand capabilities and instant turn on & turn off characteristics. Of course, with all of these ideal features, the device should be available at economical price. This dream is a challenge that will never materialize, but moving step by step that it can be approached. This paper facing these challenges through setting criteria for selecting the most suitable power devices for automotive applications such as hybrid, fuel cell and 42 V based vehicles are introduced, where theoretical and practical comparative study of three semiconductor switching devices are demonstrated (Miller *et al.,* 1998).

2. AUTOMOTIVE POWER DEVICES CHALLENGES

For most power devices applications, there are many requirements including current, voltage, switching, thermal, reliability and cost effective. In addition to these requirements, the automotive applications provide additional challenges to power semiconductor devices, such as maximum operating ambient temperature ranged from 85°C to 150° C depending on the location of the electronic system in the vehicle (Vimont, 1999). In the following section, some of the major power devices requirements are introduced.

2.1. Low On-resistance and High Current Density

Automotive applications require high current density. It can be in the range of 300 to 600 Amp per motor phase (Hartman, 1999). This level of current can hardly be cost effectively switched using single device because the silicon cost increases non-linearly with respect to the die size. Therefore, parallel devices can be a good solution to safely carry the high current. Moreover, in order to increase the energy conversion efficiency of power electronics system, it is necessary to decrease the device on resistance.

2.2. Maximum Breakdown Voltage

Device maximum voltage requirements depend mainly on its applications in the vehicle. For 42 voltage applications as an example, the standard is set and defines the allowed operating high voltage levels. The maximum voltage is 60 V, while voltages overshoot due to parasitic power stage inductances are not considered. Hybrid vehicles mostly use battery voltage in the range of 150-350 VDC. Unfortunately, up till now no voltages standards exist for hybrid or electric vehicles (Duke *et al.,* 1993). Furthermore, in motor drives and propulsion applications, the device voltage rating depends on vehicle battery and charger voltages. Additional voltage requirements may be dedicated by local inductor over shoots.

2.3. Base/Gate Drive Requirements

Bipolar Junction Transistor is a current drive device that requires high current drive circuits. Darlington transistors are more popular devices in this area because it's high current gain. MSFET and IGBT have similar gate drive requirements as both of them are voltage drive devices. So, the gate drive circuit must be able to charge and discharge device input capacitance. Also, satisfy the switching time, dead time and EMI constraints (Kazerani *et al.,* 1991).

2.4 High Temperature Applications

In general, power devices are heat sources in addition to the high operated ambient temperature produces from the automotive applications. So, the power semiconductors should support these high operating temperatures. The operating temperature may pass 175°C, where High Temperature Reverse Biased (HTRB) and High Temperature Gate Biased (HTGB) testing (Wall and Jakson, 1993). It is expected In near future, this temperature requirements will be increased up to 200O C.

3. SEMICONDUCTOR SWITCHES

There are many modern semiconductor switching devices can be used in automotive industry including

3.1 Bipolar Junction Transistor (BJT)

BJT is continuously current controlled device and increased popularity in power electronics applications. An NPN transistor is more common than PNP one because of the higher mobility of electrons. An important property of BJT is that its current gain varies with collector current and junction temperature. The current in this device can be increased with lower duty cycle within the constraints of peak junction temperature, wire bond melting and second breakdown effect. Its disadvantages include higher leakage current, higher conduction drop and reduced switching frequency. BJT switching speeds considered fast comparing with thyristors because of majority carriers in the base are almost entirely removed by negative base current (for NPN transistor). Modern high power transistors are normally comprised of multiple matched devices in parallel within a package. Power transistor applications in automotive ranged from few KW to several hundred KW size, with switching frequency up to 10-15 k Hz. The BJT with the specifications explained in Table (1) is used to represent this type of switching devices.

Table 1. BJT (TIP 132) specifications

Type		TIP 132
Maximum collector to emitter voltage		100 V
Maximum emitter current		8 A
Maximum power		70 W
H_{fe}		15000
Delay time	(t_d)	0.15 uS
Rise time	(t_r)	0.55 uS
Storage time	(t_s)	2.5 uS
fall time	(t_f)	2.5 uS

3.2 Metal Oxide Semiconductor Field Effect Transistor (MOSFET)

Power MOSFET is unipolar, majority carrier and voltage controlled device. The N channel enhancement mode device is common because of higher mobility of electrons. Because MOSFET is voltage controlled device, the gate circuit impedance is extremely high. However, during fast Turn ON and Turn OFF, the gate needs a current pulse to charge and discharge respectively. As a majority carrier device, there is no inherent delay and storage switching time like most of BJT. Therefore, MOSFET is faster than BJT. The on-resistance of a device is a key parameter that determines the conduction drop. It also increases with voltage rating α V2.5 making the device very lossy at high current. The second break down effect of the MOSFET is negligible because of its positive temperature coefficient. This device tends to be less robust from an avalanche and Forward Biased Safe Operating Area (FBSOA) stand point. Work is in progress to improve the device parameters especially its embedded body diode performance. The state of the art modules are available with 1000 V/ 300 Amp ratings. The specifications data of the selected MOSFET which is used to be studied as a resonant switching device is shown in Table (2).

Table 2. IRFP254 MOSFET specifications

Type	
Drain-source breakdown voltage (V_{gs})	250 V
On-state drain current(I_d)	23A
Maximum power(P_d)	150 W
Input capacitance(C_{iss})	2800 PF
Drain-source on resistance(R_{ds}-on)	0.14 Ω
Turn on delay time(t_d-on)	25 nS
Rise time(tr)	60 nS
Turn off delay time(t_d-off)	70 nS
Fall time($_{tf}$)	25 nS

3.3. Isolated Gate Bipolar Transistor (IGBT)

The IGBT is basically a hybrid MOS-gated turn on/off bipolar transistor that combines the attributes of BJT and MOSFET which was commercially introduced in 1983, since then its ratings and characteristics have improved significantly. It offers many advantages of BJT and MOSFET in medium power (few KW to hundred KW) and medium frequency up to 50 kHz. The device has high input impedance for the MOSFET but BJT like conduction characteristics. The trend in the development of IGBT is to reduce saturation voltage and turn off time. An impressive improvement has been achieved thanks to novel designs of the IGBT die. IGBT are widely used in medium power applications in automotives including motor drives, converters and as drivers for solenoids and relays. It is expected that IGBT will eventually oust BJT in most applications. Its specification is explained in Table (3).

Table 3. GT25Q101 IGBT specifications

Type	*GT25Q101*
Maximum collector emitter voltage (V_{ce})	600 V
Maximum emitter current (I_d)	25 A
Maximum power (P_d)	150 W
Input capacitance (C_{iss})	1400 PF
Turn on time (T_{on})	0.4 uS
Turn off time (T_{off})	0.5 uS

4. PERFORMANCE COMPARISON

4.1 Usable Frequency Versus Current

A useful way to compare the performance of different devices is to graph usable frequency versus current. What makes this so valuable is that it incorporates not only conduction loss, but also switching loss as well as thermal resistance. It also makes it easy to compare the performance of different types of devices, like IGBTs and power MOSFETs (Graf, 1999).

Beginning with the fundamental relationships:

$$P_{diss} = P_{cond} + P_{switch} = \frac{T_J - T_C}{R_{\theta JC}}, P_{cond} = I_C \cdot V_{CE(on)} @ I_C, \quad (1)$$

and

$P_{switch} = (E_{on} + E_{off}) \text{ X } f_{switch}$,

The maximum switching frequency is derived as[1]:

$F_{max} = \min(f_{max1}, f_{max2})$

$$f_{max1} = \frac{0.05}{t_{d(on)} + t_{d(off)} + t_r + t_f}, \quad f_{max2} = \frac{P_{diss} - P_{cond}}{E_{on} + E_{off}} \quad (2)$$

It is f_{max1}, a percent of switching time limitation that limits the frequency at low current; f_{max2}, a thermal limitation, limits the frequency otherwise. The fmax1 pulse width limitation rule favors small devices with their small capacitances and shorter delay times. In this case, the estimated time spent switching (the sum of delay, rise, and fall times) is no more than 5% of the total switching period. A different pulse width limit rule may be used, but it does make sense to limit the time spent switching to some percentage of the total switching period so the die has time to cool between switching transients. Above a certain current, the frequency is limited by heat dissipation due to switching and conduction losses (f_{max2}) rather than a pulse width limitation (f_{max1}). Based on the previous analysis, a performance study of MOSFET and IGBT will be introduced, as they can be considered the most suitable devices for automotive applications.Lower losses as well as lower thermal resistance $R_{\theta JC}$ result in higher maximum frequency. In general, a device that is thermally capable of the highest switching frequency is the most efficient device. Fig. 1 shows usable frequency versus current curves for IGBT and MOSFET.

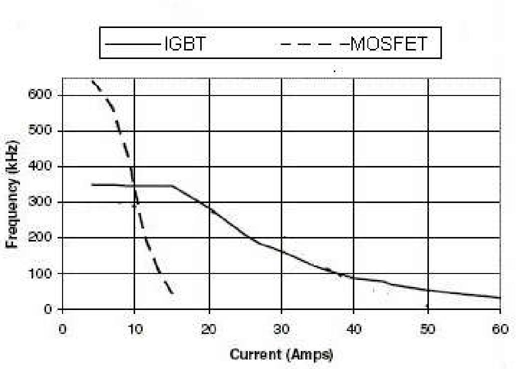

Fig 1. Usable frequency vs. current

With the same power ratings, the die area of the MOSFET is approximately three times larger in area. Device cost depends on die area, so the device with the smallest die size that meets an application's requirements is generally the least expensive choice. Now suppose we want to switch 20 Amps at 200 kHz. Either the IGBT or the MOSFET will work, but the IGBT is about one third the cost of the MOSFET because of its smaller die size. Above 37 Amps the IGBT wins, even though its die size is smaller; its junction temperature would be lower than that of the MOSFET at a given frequency. This goes against conventional wisdom, which says that a MOSFET is always more efficient than an IGBT, and that higher efficiency means higher cost. The curves in Fig. 1 warrant a few more comments. A convenient comparison to note is that the ID rating of the MOSFET (continuous conduction with the case at 25 °C) is similar to IC2 rating of the IGBT (continuous conduction with case at 110 °C), 54 and 49 Amps respectively. These w_o current ratings are similar, and the performance of each device is also similar. Both are capable of 200 kHz operation at about half their current ratings. So matching up the MOSFET ID rating to the IGBT IC2 rating is a quick way to make initial comparisons between power MOSFETs and Power IGBTs. Second, an IGBT has higher current density, which equates to lower on-state voltage and enables using a smaller die at the same power level as a high voltage power MOSFET. Due to dramatically increased on resistance with increasing breakdown voltage ratings, power MOSFETs rated at or above about 300 Volts have lower current densities than IGBTs. This is why a IGBT with a 600 Volt rating can replace a MOSFET rated at around 400 Volts or higher. The smaller IGBT die size results in a higher thermal resistance than a power MOSFET, but the junction temperature is not higher due to lower losses. Remember, thermal resistance is accounted for in the usable frequency versus current curves. Finally, different devices are best under different operating conditions. At high frequency and relatively low current, a MOSFET is usually the best choice (or you could use a smaller size IGBT). At high current, an IGBT is the best choice because conduction loss increases very modestly with increasing current, whereas the conduction loss of a power MOSFET is proportional to the current squared. At most frequency or current ranges, more than one device type might work well, so there is often more than one right answer. However, the latest generation PT IGBT will usually be the least expensive option. This very important point is the reason behind an emerging trend to replace power MOSFETs with IGBTs in high voltage, high frequency power supplies.

4.2. Switching Speeds

Turn-on characteristics of an IGBT are very similar to a power MOSFET. Turn-off differs though because of the tail current. Thus the turn-off switching energy in a hard switched clamped inductive circuit gives an indication of the switching speed and tail current characteristic of an IGBT. Fig. 2 depicts the trade off between turn-off switching energy E_{off} Within any technology, in order to reduce conduction loss, switching energy must increase, and vice versa. Only technology improvements can yield both lower conduction and lower switching losses (Manias, 1991). Figure 2 shows two technology curves, the dashed curve depicting the performance of previous generation devices, and the solid curve depicting the performance and tradeoff point of the latest generation of devices. By utilizing the latest technology, switching energy has been reduced by 30% to 50% without significantly increasing VCE (on), resulting in a high performance devices optimized for high voltage applications.

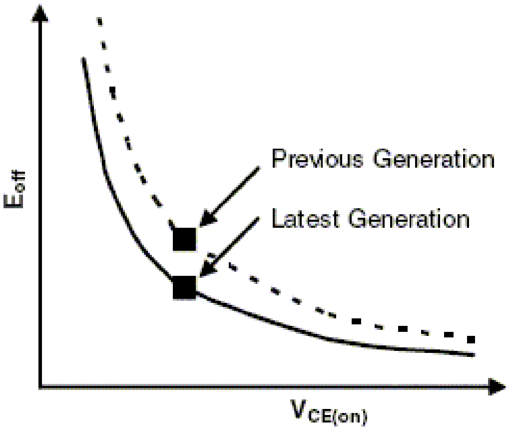

Fig. 2 Turn-Off Energy vs. VCE

5. Experimental results and discussion

In order to determine the most suitable switching device to be used in the resonant circuit the following experimental study had been performed. This study concentrates mainly on the turning on delay time and the switching device on resistance because those two factors affect the resonant frequency. Considering that the attributes of the ideal power semiconductor switch are zero power loss in the on and off states, zero power loss during switching, minimum power required to control operation, simple drive circuit requirements, never fail, easy to use and inexpensive. Hoping to approach this imaginary ideal switch three types of modern switching devices had been used and tested as resonant switching devices to demonstrate the performance of each one.

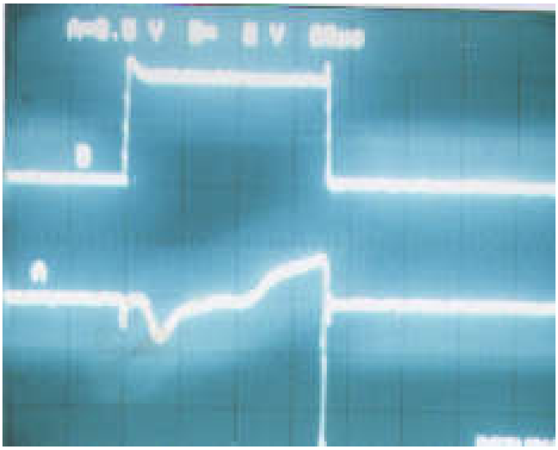

Fig. 3. BJT base to emitter voltage and emitter current.

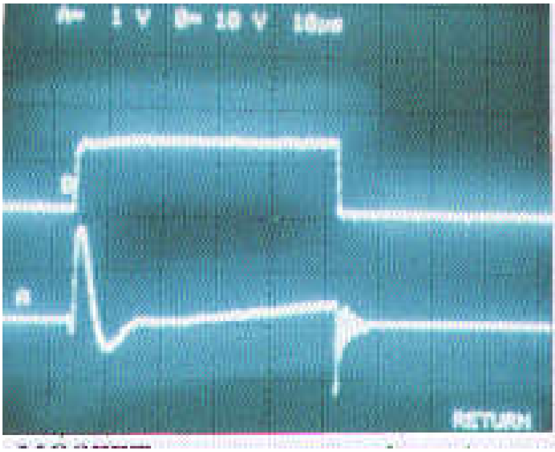

Fig. 4. MOSFET gate to source voltage and source current

The switching characteristics of TIP 132 Darlington transistor is shown in Fig. 3, which explains an expanded view of the switching period. The upper trace is the base to emitter voltage while the lower one is the emitter current. The relatively long turn on delay time can be noted because the turning on of bipolar transistor requires that the capacitance associated with base-emitter junction be charged. The resulting charge distribution required to sustain current flow results in a delay time when a bipolar transistor is turned on. This time may be in order of microseconds.

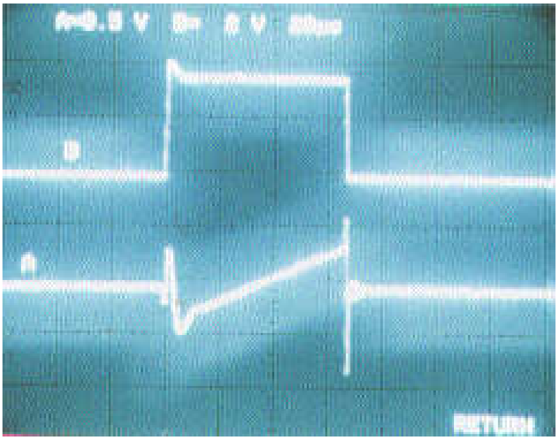

Fig. 5. IGBT gate to emitter voltage and emitter current.

These low switching speeds make such this device unsuitable for high frequency applications. Also, the bipolar transistor is a current driven device so that , for the applications requiring high current, considerable power may be dissipated in the base drive circuitry. On the other hand, it is noticed that the rate of the current increase -when the BJT is on- can be considered high. This is because of the low on resistance of the device. The switching speeds are directly related to delays within the structure and to the capacitance which must be charged and discharged. The switching time in the power MOSFET is determined by the gate capacitances and the current available from the drive circuitry. So, a perfect design of the gate drive circuit, makes it has the capability to supply charging current and sink discharging current of the MOSFET input capacitances. This in turn will increase the switching speeds of the power MOSFET. Figure 4 explains the IRFP 245 switching characteristics. The upper trace is the gate to source drive voltage while the lower one shows the MOSFET drain current including the in package freewheeling diode. This current is the resonant inductor current at switching period. It is noticed that turning on time of the power MOSFET is very fast compared to the BJT. On the other hand, it is clear that the rate of MOSFET source current -which is the resonant inductor current at the switching period- is low compared to that rate in the BJT. In other words, it can be said that the BJT has a slow switching speeds but the current increase during turn on period is high due to its low on resistance. While the characteristics of the power MOSFET is different as, its switching speed is fast but the current increase is low because of its high on resistance. Trying to combine both of BJT and MOSFET attributes, the IGBT is tested. The results of this test is shown in Fig. 5 that shows switching instants of IGBT. It can be noticed that the IGBT turns on as fast as MOSFET and has the low conduction resistance. With these two advantages the IGBT is more suitable as a switching device.

6. Conclusion

1. Power semiconductor devices play a major role in development of automotive power electronics. Most of advanced devices had been demonstrated and evaluated.
2. BJT, MOSFET and IGBT devices have made significant advances in meeting the automotive power electronics systems. These three devices were compared from most important points of automotive applications.
3. Experimental results explain that the IGBT has the advantages to be suitable in automotive applications as it combines the attributes of both BJT and MOSFET

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