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# A STUDY OF s NEW POWER SEMICONDUCTOR INSULATED GATE BIPOLAR TRANSISTOR (IGBT) CHARACTERISTICS AND ITS APPLICATION TO AUTOMOTIVE IGNITION

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## ABSTRACT

Assessment has been made of the problem of the on- resistance and temperature effects in the three terminal power transistor combinations, such as Darlington-types or IGBT. The IGBT is a device in which the drain of the MOSFET feeds the bipolar base in a monolithic (IC and Power on the same chip) to give it both the MOS and bipolar advantages. The high temperature operating characteristics of the device are discussed and compared to that of power bipolar transistor. Unlike the power bipolar transistor whose operating current density shows current crowding at above forward collector current of 4Amps and forward voltage drop above 0.4V, the IGBT is found to maintain its high current density above forward collector of current 1Amp (or a forward voltage drop above 1.2V). The results also indicate that these devices (IGBTs) can be interdigited (paralleled) without current hogging problems if the forward conduction occurs at foward voltage drops in excess of 1.2V, and this makes it the best candidate for automotive ignition power switches.

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## 1. Introduction

The IGBTs [1,2,3] are a new class of power semiconductor devices that evolved through the use of optimal combination (integration) of VDMOS and power bipolar transistor technologies. The aim is to achieve a high power device having the advantages of high input impedance and high speed characteristics of a Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET) with high conductivity characteristic (low saturation voltage) and low ON-state resistance of the bipolar product, intended particularly, for use in the medium to high power range. This is due to the fact that there is now increasingly more industrial need for high power transistors with low power dissipation and, are capable of operating at elevated temperatures.

The cross-section in Fig. 1 shows that the structure of IGBT is very similar to that of a standard vertical power MOS (Fig. 2), but in an IGBT, the substrate is $p^+$-type anode which makes a *p-n* junction with $n^-$-drain. The very wide $n^-$-$p^+$ "anode" junction created, dramatically lowers the on-resistance because during conduction, holes coming from the $p^+$-substrate are injected into the $n^-$-layer which is lightly doped to provide it with the most valuable reverse blocking property. Due to the sandwiched layer of the device, the area with the extra $p^+$-layer forms a *p-n-p* bipolar junction transistor (BJT) which controls the fall time of the device (Fig. 1b). More detail about these devices can be found in reference [9-11,14-16].

The open base switching of the BJT portion of the device terminates with the recombination of excess minority carriers. Consequently the turn-off is dominated by the lifetime of the minority carriers in the $n^-$-region. The disadvantage of the IGBT is longer fall time than the power MOS devices [4]. However, with respect to BJT devices, the fall time is about the same because, by using appropriate techniques, the fall time of an IGBT can be made shorter than approximately 2μs (Fig. 3). In order to improve the fall time in IGBTs, techniques such as electron beam irradiation and doping with life time killers (heavy metals doping) have been used to reduce the life-time of minority carriers [5,6,7,8].

Structural design changes by the insertion of a $n^+$-buffer layer between $n^-$ and $p^+$ have also been introduced. The optimization of these techniques in IGBT has allowed the best trade-off between switching speed, current capability and ruggedness to be achieved.

## 2. The temperature effects on the IGBT characteristics and the turn-off time

Power devices are fundamentally temperature dependent. Since all power devices are normally operated at elevated temperatures, it is important to determine how their performance varies with temperature. Fig. 4a shows the circuit used to obtain the static I-V characteristics of the IGBT. The current and voltage were obtained using multimeter, while the temperature readings were obtained using a temperature meter with a thermocouple attached to the device mounting. Fig. 4b shows the IGBT true I-V static characteristics with equilibrium temperature curves. The curves were plotted from the data taken with the IGBT mounted on a forced air cooled heat sink measuring 70x120*mm*. It was observed that even with this type of system (air cooled), the temperature rise was sufficient to make the true static curves to slope upward, showing a dramatic increase in the output slope conductance. Since these very high power devices are of special importance for D.C. power supplies, the long thermal time constant, typically 20 milliseconds, is of typical importance. For automotive ignition switches, this will not be a problem because switching is of the saturation type [9,10].

Although the switch-off (fall-time) can be reduced substantially as mentioned earlier, it was observed (Fig. 5) that as the temperature rises, the turn-off ($t_{off}$) also increases, from 2μs at 25°C to 6μs at 200°C, but since automotive ignition is an *one-off* action, the device heating will not be a problem.

## 3. Temperature effects on forward conduction characteristics

A large gate bias voltage was applied to the IGBT. The conductivity of the inversion channel under MOS-gate became very high. Hence, the forward current in the IGBT became insensitive to the gate bias voltage. The forward I-V characteristics were similar to those of *p-n* junction diodes. Fig. 6 shows a typical set of forward voltage drop characteristics measured at temperatures ranging from 20°C to 200°C, at various fixed forward currents, and gate bias of 25V.

This can be compared with the same plots for power bipolar transistor (Fig. 7). (We will not concern ourselves with MOS temperature characteristics as it is mainly used as a driver [11].)

The power bipolar transistor in Fig. 7 show two very important features, first an almost steady increase in the forward voltage drop with temperature rise for the currents below 7*Amps*. Above 7*Amps*, a decrease followed by a minimum and then an increase was observed. This can be compared with the IGBT characteristics (Fig. 6) which show a continuous decrease in forward voltage with temperature rise throughout - a great advantage in terms of high power applications. Such behaviour of BJT and to some extent IGBT are similar to *p-n* diode operating at high injection level currents [12] and is given by

$$I_{Anode} = \frac{2eDA}{L} n_i exp\left(\frac{eV_A}{2kT}\right) \qquad (1)$$

where D and L are the ambipolar diffusion coefficient and diffusion length, respectively, A is the diode area, e is the electronic charge, *k* is the Boltzmann's constant, T is the absolute temperature, and $n_i$ the intrinsic carrier concentration normally given by [13]

$$n_i = AT^3 exp\left(-\frac{E_g}{kT}\right) \qquad (2)$$

making Eqn. (1) an highly temperature dependant implying that power dissipation will increase with rise in temperature. This could lead to thermal runaway and current crowding. ($E_g$ is the semiconductor energy gap.) This has been documented in detail in a paper by Rabah, K V O [14].

In order to understand more about the thermal behavior of these transistors, an Arrhrenius plot of the collector (BJT) and anode (IGBT) currents at various forward voltage drops was undertaken. results are presented in Figs. 8 and 9, respectively. Unlike the power bipolar whose operating current density shows current crowding at above forward collector current of 4*Amps* and forward voltage drop above 0.4*V*, the IGBT (Fig. 9) is found to maintain its high current density above forward collector current of 1*Amps* (or a forward voltage drop above 1.2*V*). This result indicates that the IGBTs can be interdigited [10] (i.e., paralleling many devices in a monolithic form to form a single high power device), without current hogging problems if the forward conduction occur at forward voltage drops in excess of 1.2*V*. This then makes it the best candidate for automotive ignition power switches.

The reason for the IGBT's better temperature performance could be due to another inherited advantage from the MOSFET characteristics — that is, MOSFETs are related to negative temperature coefficient of their drain [15] which seems to effectively cancel out the positive temperature coefficient of the bipolar collector to give IGBTs an almost flat forward conduction characteristic. It is important to interface a temperature sensor device with the power IGBT to give warning at a very high power level/temperature range or shut the system down if the device is likely to exceed its temperature limit.

## 4. IGBT performance and other advantages

Since IGBTs are natural evolution of power MOS in high voltage, high current applications, they overcome the drawback of high voltage power MOS which have an unacceptably high value of $R_{ds}$(on) [15,16]. Further, they can handle current density over two times greater than bipolar devices under similar operation conditions with limited deterioration in operational characteristics coupled with the advantage of the MOS-gate drive simplicity (i.e., high-input impedance feature).

The low-input gate current required to control IGBT devices makes the size of components in the gate drive circuits sufficiently small, so that these devices are now amenable to integration with CMOS logic gates technology [2]. Additionally, the fast moving world of *smart electronics* is likely to include integrated system control expert circuitry (see Fig. 10) — an intelligent, reliable semiconductor *smart* power switch to include, for example, current and temperature sensing devices (to ensure that the power device does not exceed both its maximum allowable current and temperature), on the same chip as the high power IGBT [17,18,19,20]. Such expert systems are also very important in

applications where power devices are at risk of failing, because of heating (over-current), and disrupting vital controls, for example, in medical equipments, in nuclear industries, and in aeroplane's control systems.

This (monolithic integration) has created the opportunity to obtain a large decrease in component count, resulting in a reduction in system cost, size and weight. In addition, the small number of interconnects enhances system reliability. These features have created an upsurge in power electronics applications in motor drives and automated controls like robotics in industries, apart from the power automotive ignition.

An automotive ignition switch must meet certain specifications concerning voltage and current ratings, minimum energy handling capability in case of spark plug disconnection and driving requirements over the whole operating temperature range. The power IGBTs, from the above analysis, have been shown to be the best candidate. Table 1 lists IGBT characteristics which make these devices well suited to automotive ignition and also compares them with a typical automotive ignition bipolar Darlington.

## 5. Conclusion

IGBTs are high power switches which work with a very high current density. The peculiar IGBT structural characteristics can easily be exploited to lend themselves to future development in similar ways to those made in power MOSFET technology. These include low threshold gate voltage for easier driving and, also integrated current sensing to form an integrated smart power control circuitry. The drive simplicity coupled with excellent ruggedness make IGBTs ideal (solution) for automotive ignition power switching.

| IGBT | Bipolar Darlington |
|---|---|
| voltage driven | current driven |
| purely capacitive input impedaance no DC current required | low input impedance DC current required |
| simple drive circuitry | complex drive circuitry |
| predominantly negative temperature coefficient of anode current | positive temperature coefficient of collector current |
| low on resistance | high on resistance |
| high breakdown voltage | low breakdown voltage |
| higher current density | lower current density |
| more extended FBSOA & RBSOA | poor FBSOA & RBSOA |

TABLE 1 Comparison of IGBT and bipolar Darlington (FBSOA: Forward bias safe operating area and RBSOA: Reverse bias safe operating area) [10].

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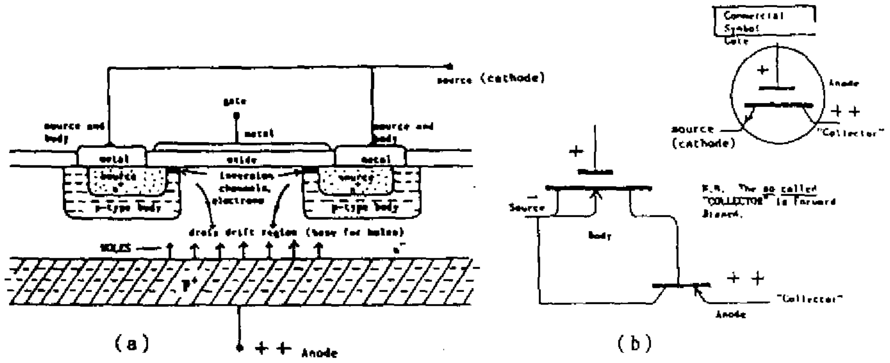


Fig. 1 Schematic of an IGBT power transistor structure

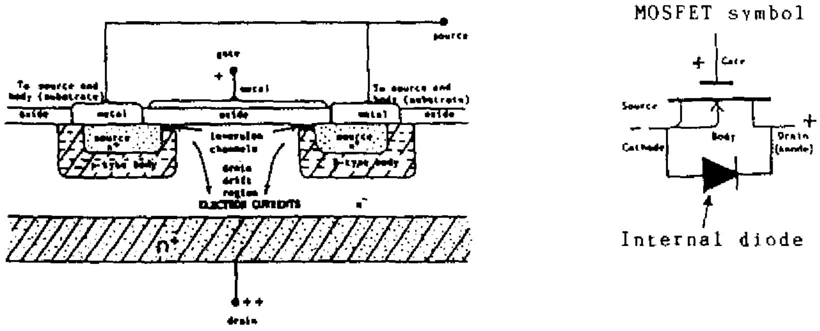
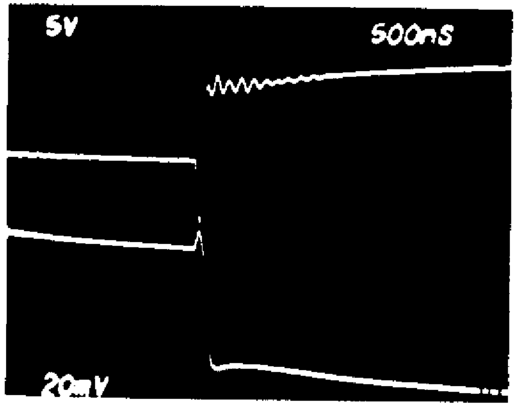


Fig. 2 Schematic of a vertical DMOS power transistor structure



**Upper trace:**
**Input voltage**

**Lower trace:**
**Anode current**
**(probe 5A/div.)**

Fig. 3 Turn-off waveform of an IGBT.

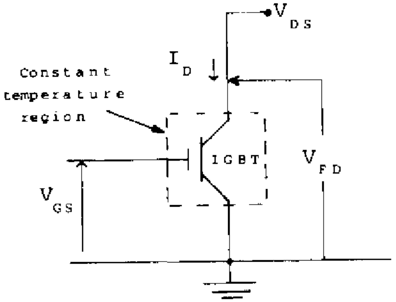


Fig. 4a Circuit used for transistor thermal study.

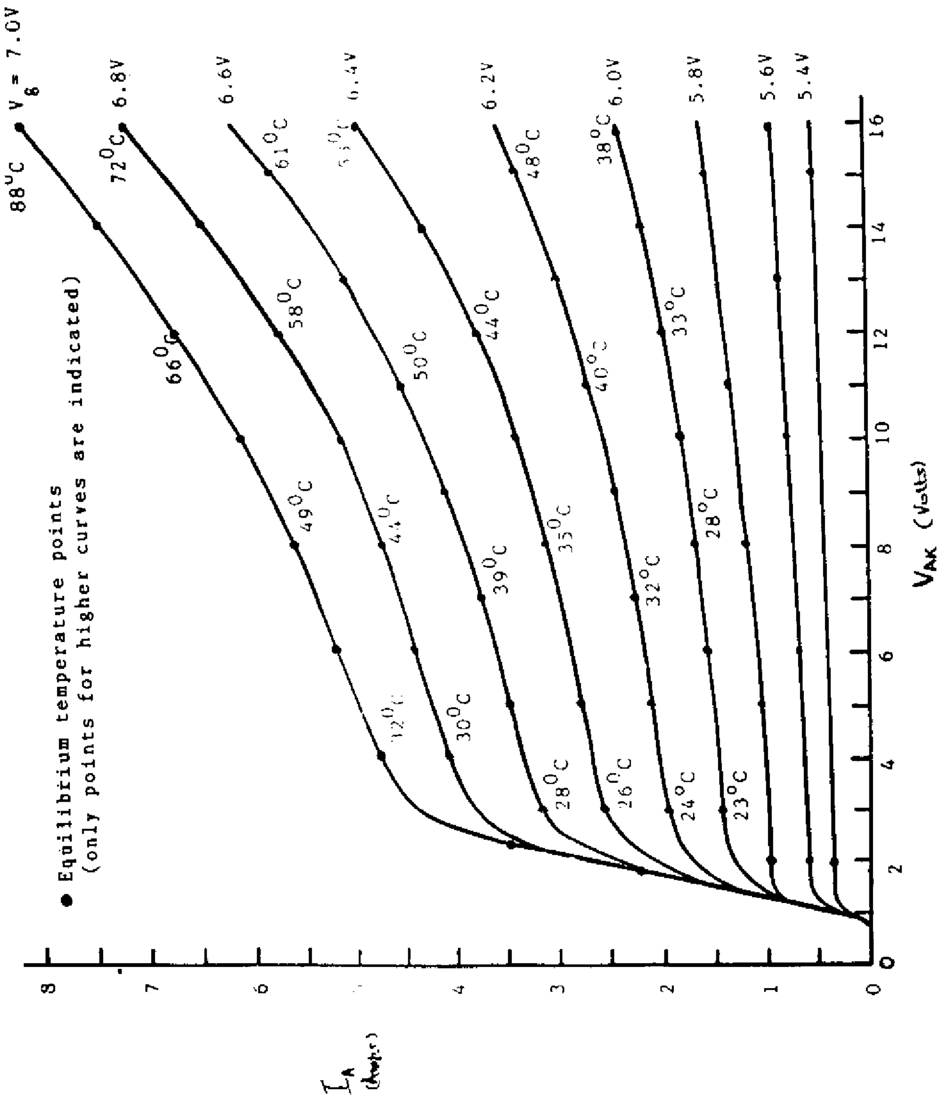


Fig.4

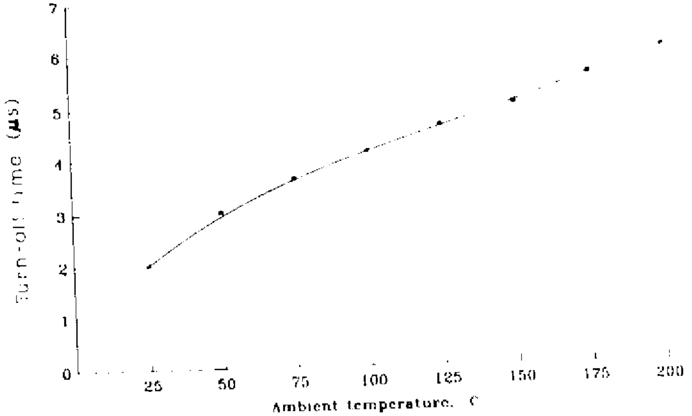


Fig. 5 IGBT temperature dependence of turn-off time

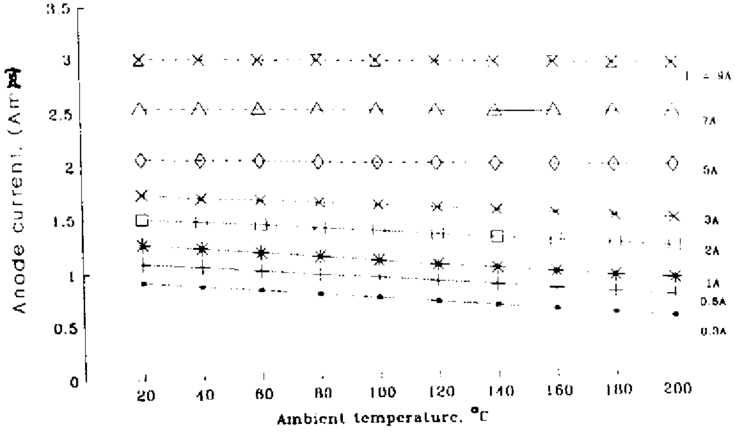


Fig. 6 IGBT forward conduction characteristics

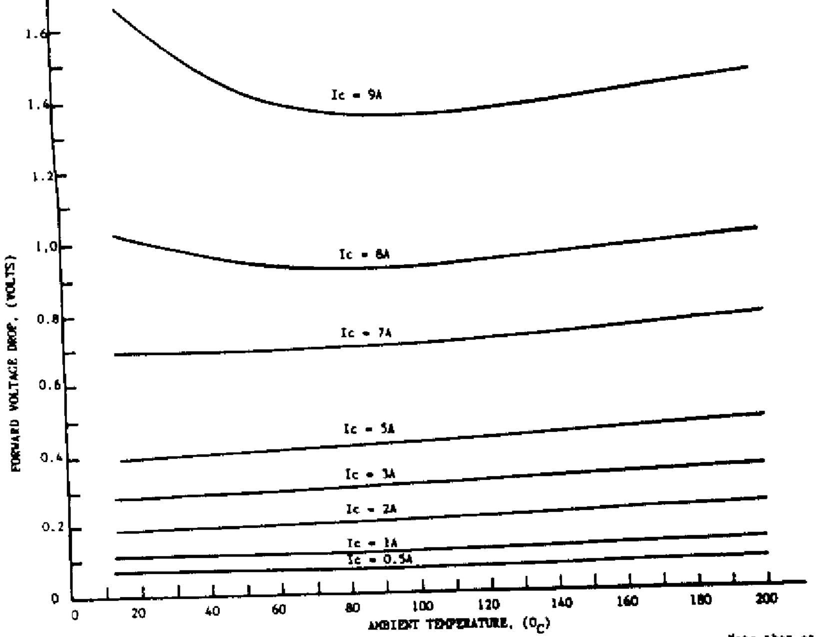


Fig. 7 Change in BJT Forward voltage drop with increasing temperature. Note that at a forward current of 8A, the forward drop becomes more temperature dependent.

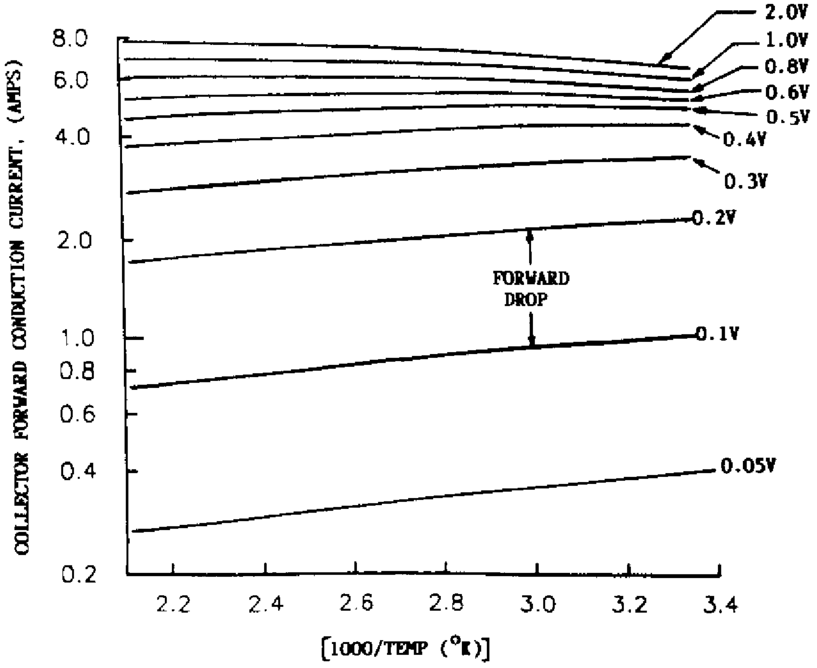


Fig. 8 Arrhenius plot of BJT forward conduction current as a function of temperature.

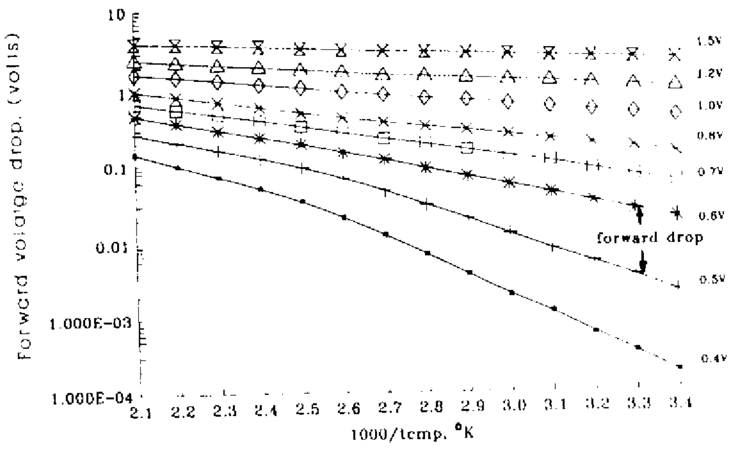


Fig. 9 Arrhrenius plot of IGBT anode currents

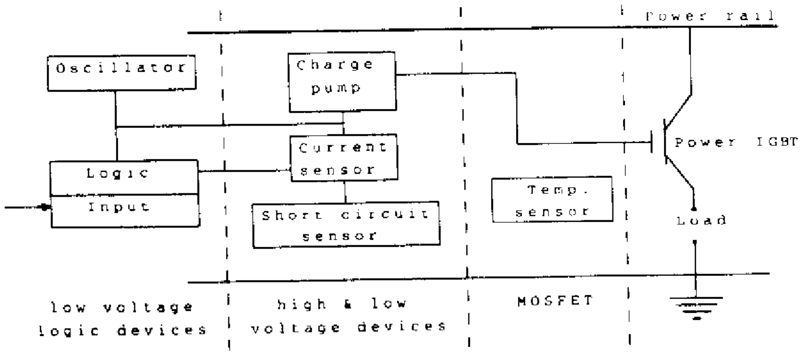


Fig. 10 Smart power switch [11,19].