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Passive Transient Voltage Suppression Devices for 42-Volt Automotive Electrical Systems

Z. John Shen

Dept of Electrical and Computer Eng., The University of Michigan-Dearborn, USA

ABSTRACT

New 42-volt automotive electrical systems can provide significant improvements in vehicle performance and fuel economy It is crucial to provide protection against load dump and other overvoltage transients in 42-volt systems. While advanced active control techniques are generally considered capable of providing such protection, the use of passive transient voltage suppression (TVS) devices as a secondary or supplementary protection means can significantly improve design flexibility and reduce system costs This paper examines the needs and options for passive TVS devices for 42-volt applications The limitations of the commonly available automotive TVS devices, such as Zener diodes and metal oxide varistors (MOV), are analyzed and reviewed A new TVS device concept, based on power MOSFET and thin-film polycrystalline silicon back-to-back diode technology, is proposed to provide a better control on the clamp voltage and meet the new 42-volt specification Both experimental and modeling results are presented Issues related to the temperature dependence and energy absorbing capability of the new TVS device are discussed in detail. It is concluded that the proposed TVS device provides a cost-effective solution for load dump protection in 42-volt systems.

Keywords 42-volt systems, TVS, automotive power electronics, load dump, protection circuits

1. Introduction

Increased power demands on vehicle electrical systems, in addition to the automotive industry's need to improve fuel economy and emission, are making current 12/14-volt automotive electrical systems inadequate. The automotive industry worldwide is developing new 42-volt or dual 14/42-volt power system solutions (also referred to as the 42-volt *PowerNet*) to increase electrical power and efficiency and to enable additional loads and new technologies[1-3] New 42-volt architectures could improve fuel economy in two ways. The first is through mass reduction of wire harnesses and motors. The second is by enabling new technologies that will increase efficiency of vehicle systems. Power electronic circuits and devices form the foundation of the 42-volt power generation and distribution systems To maintain a low voltage rating and therefore affordability of the circuits and devices, it is essential to protect these electrical systems from overvoltage transients in the automotive environment

The automotive industry has recently established specifications on 42-volt bus voltage regulation, which is significantly tighter than the present 12/14-volt systems[3] Table 1 summarizes the newly proposed 42V bus voltage specifications The nominal bus operating voltage is 42 volts The maximum operating voltage and maximum dynamic overvoltages are 48 and 58 volts respectively

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Corresponding Author johnshen@umich edu, Tel +1-313-593-5525, Fax. +1-313-593-9967

Table 1 42-volt PowerNet voltage specifications

Symbol	Definition	Value (volt)
Vop	Nominal bus operating voltage	42
Vmin, op	Minimum bus operating voltage	30
Vmax, op	Maximum static operating voltage	48
Vmax, dyn	Maximum dynamic overvoltage	58

The maximum dynamic overvoltage occurs during the notorious load dump transient, a voltage spike that appears on the power bus when a fully loaded alternator/generator suddenly loses its load (for example, when a charging battery is inadvertently disconnected). This voltage spike, if not suppressed, could exceed over a few hundred volts and destroy many electronic components connected to the power bus. In the present 12/14-volt automotive systems, load dump protection is usually provided by transient voltage suppression (TVS) devices, such as Zener diodes or metal oxide varistors (MOV), located inside the alternators (centralized protection) or individual electronic modules (distributed protection). These TVS devices suppress load dump transients and clamp the bus voltage below the maximum allowable values during the decay process of the alternator field current The voltage and energy requirement on the TVS devices, being an important part of the automotive industry standards (i e , *SAE J1113* [4]), is based on the 14-volt system requirement and the characteristics of Lundell alternators, which are exclusively used in the 12/14-volt systems.

Most of the newly proposed 42-volt power generation systems employ three-phase induction or permanent magnet synchronous machines instead of Lundell alternators to achieve higher power output and efficiency as well as to implement integrated starter generator (ISG) function[5] Fig 1 illustrates a typical 42/14-volt dual-voltage integrated starter generator system The control system usually adopts advanced active control algorithms such as field-oriented or vector control[5], or switching mode rectifier[6] for superior dynamic response, and hence features a small but finite control loop time ranging from several to several tens of milliseconds. Ideally the control system is able to detect and react to a load dump event within the control loop time window However, the control loop time is determined by a series of complicated tradeoffs between several design factors, including but not limited to, DSP speed, sensor signal sampling rate, complexity level of the control algorithms, and inverter/converter PWM frequencies, etc. A smaller control loop time is generally achieved at the expense of cost and complexity of the control system The requirement of designing an unusually small control loop time specially for load dump protection can be significantly relaxed if a passive TVS device is used to serve as a secondary or supplementary protection means[8], as shown in Fig 1 The design complexity and overall cost of the control system can also be considerably reduced. In case of a load dump event, the passive TVS device will instantaneously clamp the bus voltage below the specified maximum dynamic overvoltage (i e 58 volts) for a short time period. This will give the active control system enough time to detect and react to the load dump event Given sufficient energy absorbing capability, a TVS device may also serve as a redundant protection measure in case the controller malfunctions or fails Section 2 continues the discussion on the needs for such TVS devices in more detail

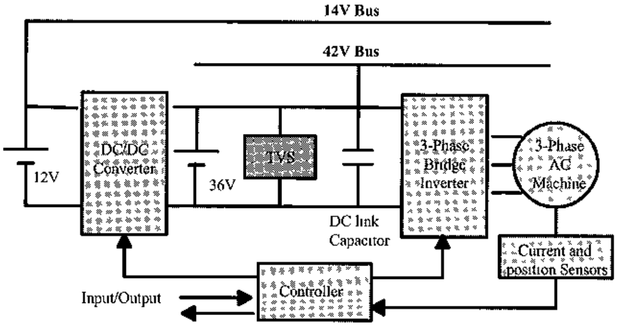

Fig 1 A 42/14-volt dual-voltage integrated starter generator system.

Currently there are two types of TVS devices available for load dump protection in 14-volt automotive systems Zener diodes[7, 9] and MOVs[10]. Neither type of devices is suitable for 42-volt automotive systems due to the large variation in their clamp voltages, as will be explained in Section 3 A new TVS device concept, based on power MOSFET and thin-film polycrystalline silicon *back-to-back* diode technology, is described in Section 4. The experimental and modeling results of this TVS device as well as issues related to its temperature dependence and energy absorbing capability are discussed in Section 5. It is concluded in Section 6 that the new TVS device, combined with effective control systems, provides a cost-effective solution for load dump protection in 42-volt systems.

2. Requirements for 42-Volt TVS Devices

14- and 42-volt automotive systems impose different requirements on passive TVS devices because of the differences in power generation methods, electrical system architectures, and bus voltage specifications. It is useful to compare the unique needs for 14- and 42-volt TVS devices in terms of clamp voltage and energy capability.

First, in a 14-volt system the nominal bus voltage is close to 14 volts while the electronic subsystems are capable of withstanding a voltage ranging from 40 to 60 volts. The allowable margin of voltage variation between the nominal and maximum dynamic bus voltages ranges from 186% to 326% of the nominal voltage. On the contrast, the nominal bus voltage is 42 volts and the maximum dynamic voltage is 58 volts in a 42-volt system[3]. The allowable margin of voltage variation between the nominal and maximum dynamic bus is merely 38% of the nominal bus voltage in 42-volt systems. Hence the new 42-volt systems require TVS devices with a much more accurately controlled clamp voltage.

Secondly, 42-volt systems are typically designed for a power rating of 4 to 10 kW while most 14-volt Lundell systems generate no more than 1 kW of electric power. However, the actual energy capability requirements on the 14- and 42-volt TVS devices depend not only on the system power ratings but also the time duration when a load dump event is in effect. 14-volt alternators are controlled by relatively simple voltage regulator ICs or modules. During a load dump event, the field current of the alternator will decrease to zero under the control of the voltage regulator. Such a field decay process typically lasts up to 500 milliseconds to fully deenergize the field coil of the alternator. A TVS device will have to be able to absorb the energy during this long decay process for the 14-volt alternator. On the other hand, 42-vlot systems are controlled by much more sophisticated control algorithms and therefore take much shorter time to respond to a load dump event. Therefore, it is necessary to determine the time window during which a 42-volt TVS device needs to suppress the voltage transients and absorb the energy.

Thirdly, in 42-volt power systems such as the one shown in Fig. 1, a large DC-link capacitor of a few tens of mF is usually used as the filter to supply the large initial starter cranking current. The DC-link capacitor, in parallel to the proposed passive TVS device, will help suppress voltage transients on the power bus to a certain extent and relax the energy requirements on the 42-volt TVS device. The time duration Δt required for charging the capacitor C from an operating voltage V_{op} to the maximum dynamic voltage $V_{max,dyn}$ (i.e., 58V) is given by

$$C\frac{\Delta V}{\Delta t} = I_{charge} \tag{1}$$

$$\Delta V = V_{\max,dyn} - V_{op} \tag{2}$$

where, I_{charge} is the battery charging current when the load dump event occurs. For example, given a battery charging current I_{charge} of 100 ampere, a bus operating voltage V_{op} of 48 volts, and a capacitance C of 25 mF, it takes only 2.5 milliseconds to reach the maximum dynamic bus voltage of 58 volts.

If the loop time of the control system is less than Δt, there would be no need for passive TVS devices. The control system would have reduced the charging current before the maximum allowable bus voltage is reached. However, a passive TVS device connected to the power bus will permit the use of an otherwise too large control loop time and/or a smaller and less expensive DC-link capacitor. This will help reduce the overall system cost significantly. The TVS device will suppress the load dump voltage transients and absorb the energy. Fig. 2 demonstrates the load dump transient voltage as a function of time for a DC-link capacitor of 10 mF, 25 mF, and 50 mF, respectively. A charging current of 100 ampere and a bus voltage of 48 volt are assumed at the beginning of the load dump event. It takes 1, 2.5 and 5 milliseconds to reach the maximum dynamic overvoltage limit of 58 volt for the three capacitances respectively. If the loop time of the control system exceeds these limits, a passive TVS device should be used to clamp the bus voltage at 58 volts and prevent it from further increasing until the control system effectively reduces the charging current.

Finally, a TVS device may also serve as a backup or redundant protection means for load dump events in case

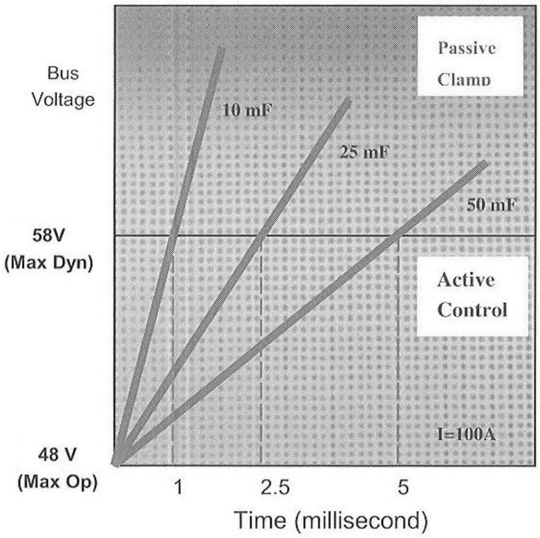

Fig. 2. Load dump transient voltage as a function of time for various DC-link capacitors.

the control system fails at the same time. However, it should be noted that such an application would require the TVS device to sustain a much higher energy pulse than what was discussed previously. Moreover, 42-volt alternators, which are very similar to the simple and inexpensive 14-volt alternator/regulator configuration, have been proposed for low-end 42-volt vehicle products. Due to the lack of sophisticated control systems, these 42-volt systems may have to entirely rely on the use of passive TVS devices to provide load dump protection, resulting in a more stringent requirement on the energy capability of the TVS devices.

3. Evaluation of Exisiting TVS Technologies

Currently there are two types of TVS devices available for 14-volt automotive systems to provide load dump protection: silicon-based single-junction Zener diodes[9] and zinc oxide-based MOVs[10]. Even though Zener diodes and MOVs operate on different physical mechanisms, neither seems to be suitable for 42-volt automotive systems due to the large variation in the clamp voltages.

The large variation in the clamp voltage of a Zener diode is mainly due to the large positive temperature coefficient of its avalanche voltage. It is a well-known physical phenomenon that the avalanche breakdown voltage of a silicon diode increases with increasing temperature[11]. Zener diodes designed for 42-volt applications have been reported recently [7]. However, it was shown that the breakdown or clamp voltage of these 42-volt Zener diodes increases roughly from 54 to 64 volts (at a current of 50 A) when the ambient temperature increases from –50°C to 175°C. This is well beyond the range defined by the new 42-volt specifications[3]. The actual maximum junction temperature may well exceed 175°C since the load dump energy absorbed by the diode heats up the junction quickly. Consequently, the variation in the clamp voltage of the Zener diodes will be even larger when they are actually engaged in suppressing load dump transients.

On the other hand, a MOV has a nearly zero temperature coefficient for its clamp voltage. The large variation in the clamp voltage of a MOV is mainly due to the inherent physical mechanism it operates on. Current conduction mechanism of MOVs is based on tunneling currents between ZnO grains through intergranular barriers[12]. A higher electric field and thus a higher voltage are needed to induce a higher tunneling current. Consequently, MOVs demonstrate very resistive current-voltage characteristics in the clamp region, resulting in a wide range of the clamp voltage. For example, a typical MOV (V33ZA05[10]) demonstrates a clamp voltage of 50 volts at a current of 100 mA. However, the same MOV shows a clamp voltage well above 100 volts when the current increases to 50 A.

4. A New MOS-TVS Device Concept

In this paper we propose a new TVS concept based on power MOSFET and thin-film polycrystalline silicon *back-to-back* diode technology to reduce the variation in clamp voltage and meet the new 42V specifications.

Semiconductor industry has long been using polysilicon back-to-back diode strings in active power switching devices to improve their surge handling capabilities[13, 14]. Fig. 3 depicts the circuit and device structure of such a diode string. Compared to single junction silicon diodes, polysilicon back-to-back diode strings reduce variation on the clamp voltage for several reasons. First, the reverse breakdown voltage of each diode is between 6 to 7 volts, right into the range where a relatively small positive temperature coefficient is observed than in any other voltage ranges. Second, the forward voltage drop of each

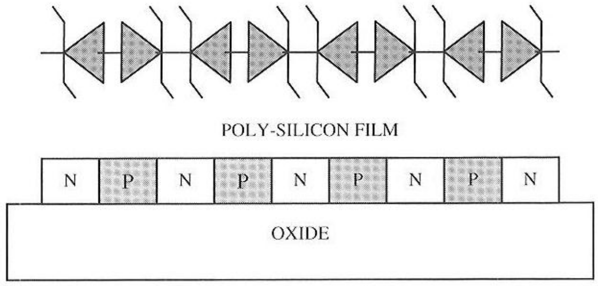

Fig. 3. Polysilicon back-to-back diode string.

diode has a negative temperature coefficient. Therefore it is possible to achieve zero temperature coefficient for the total clamp voltage of the back-to-back diode string. Third, the breakdown voltage and its temperature coefficient of the diodes can be adjusted by controlling the Boron dose in the ion implantation process.

Fig. 4 depicts the circuit scheme and die photo of the proposed new TVS device. The new TVS device is basically a two-terminal power MOSFET with an integrated drain-gate clamp back-to-back diode string and an integrated gate resistor (located at the upper-right corner of the device layout). The distinction between this TVS device and conventional drain-gate clamped MOSFET is that this device has neither an external gate terminal nor an internal gate pad. The absence of gate pad makes it possible to assemble the TVS device into a package with a high thermal capacitance and a low thermal resistance. The breakdown voltage of the drain-gate clamp diode string is designed at 52-53 volts for a current of 100mA. The gate resistor is chosen to be 10-20 kΩ. There is also another back-to-back diode string between the gate and source of the MOSFET to protect the gate oxide from electrical overstress. The breakdown voltage of this gate-source diode string is roughly between 10 and 20 volts.

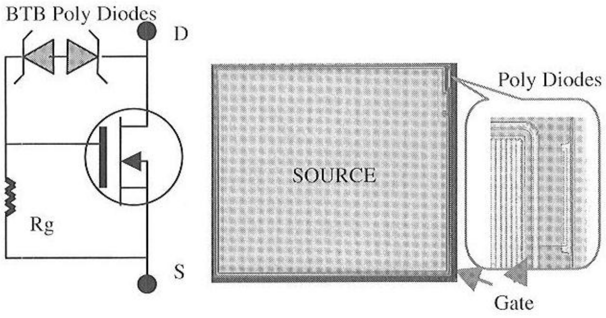

Fig. 4. Concept of the power MOSFET-based TVS device.

Both the drain-gate and gate-source clamp diodes are back-to-back diode strings made in polysilicon films to minimize temperature variation.

The breakdown voltage of the MOSFET is designed to be higher than that of the drain-gate clamp diode string. If the voltage between the drain and source of the MOSFET is below the clamp voltage of the drain-gate diodes, the TVS device is inactive and does not interact with the rest of the electrical distribution system. When the voltage between the drain and source of the MOSFET exceeds the breakdown voltage of the drain-gate clamp diodes, the diodes start to conduct a current through the built-in gate resistor to the source. The diode current will raise the voltage at the internal gate of the MOSFET through the gate resistor. When the voltage at the internal gate of the MOSFET exceeds its threshold voltage, the MOSFET switches into a conduction mode in the saturation region. A power MOSFET can absorb much more energy in a conduction mode than in an avalanche mode.

During the process of transient voltage suppression, the TVS device itself will be heated up and eventually approach the intrinsic temperature of the blocking PN junction. At that point the device will fail and cannot absorb any more energy. The energy capability of the TVS device is essentially limited by the actual peak junction temperature during a load dump event. To maximize the energy capability of the TVS device, it is desirable to place the TVS silicon chip into an electronic package that can quickly remove the heat from the junction and keep the junction temperature from increasing. Traditional power MOSFET packages, such as TO-220 and DPAK, rely on using wire bonds on the top surface of devices to provide electrical connections. However, the wire bonds do not serve as an efficient thermal path. The heat generated at the device junction is mainly transferred to the lead frame of the package through the bottom surface of the device. It is advantageous to develop a new package for the TVS device with a direct front metal contact to dissipate the excessive heat generated during the load dump transient and enhance the energy capability. A front-metal/silicon/back-metal sandwich-type of package, similar to the *PRESSFIT* type of package for diodes, is proposed for the new TVS device, as shown conceptually in Fig. 5. The package can be implemented with either solderable front metal or simply pressure contact method.

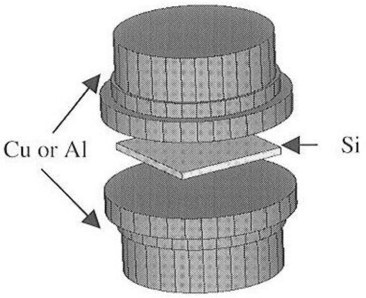

Fig. 5. Proposed package for the new TVS device.

The absence of gate pads in the new two-terminal TVS device, as shown by the layout in Fig. 4, makes it easier to implement such a new sandwich-type package. Avoiding the use of bond wires not only improves energy capability but also minimizes the parasitic inductance and resistance of the package, which may also be critical for load dump protection operation.

5. Experimental Results and Discussion

To prove the concept of the new TVS device, we have first investigated the proposed circuit constructed with discrete components. A commercially available 60-volt power MOSFET in a standard TO-220 package, two 50-volt clamp diodes and a 10 kΩ gate resistor are connected to form the circuit shown in Fig. 4. A traditional 14-volt automotive load dump tester is used to conduct the experiment. The 14-volt load dump tester is basically made of a large capacitor and a series resistor. The capacitor is first charged to a certain voltage higher than the breakdown voltage of the device under test (DUT), and then discharged through a series resistor and the DUT. While the tester reproduces a load dump event in 14-volt alternator systems reasonably well, it may not realistically represent the case of the more complicated 42-volt power generation systems. Nevertheless, the 14-volt load dump tester still provides a useful way of characterizing the new TVS device in terms of its functionality and energy capability. It should be pointed out that the capacitance and resistance values of the 14-volt load dump tester need to be reduced to provide a much smaller time constant for 42-volt testing (a few ms for 42-volt systems vs. a few hundred ms for 12-volt systems). Fig. 6 demonstrates the current and voltage waveforms of the TVS circuit under a load dump test. The time scale is 2 milliseconds per division, and the scales for the current and voltage are 20 amperes and 20 volts per division respectively. It is evident that the clamped MOSFET suppresses the transient overvoltage for a current as high as 60 A. The initial increase of the clamp voltage is mainly attributed to the shunt current sensing resistor between the ground and the source of the MOSFET.

A monolithic prototype of the proposed TVS device has also been designed and fabricated using a conventional power MOSFET process. The device layout is shown in Fig. 3. The die size is 115 x 160 mil^2. The clamp diodes and gate resistor take less than 1% of the total die area. Fig. 7 shows the measured clamp voltage of the monolithic TVS device at a current of 100 mA under various ambient temperatures. The breakdown voltage of a 42-volt Zener diode reported in [7] is also plotted on the same graph for comparison. It is clearly shown that the

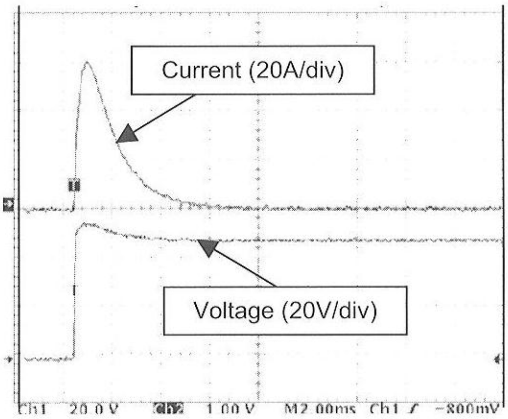

Fig. 6. Load dump test waveforms of the proposed TVS circuit.

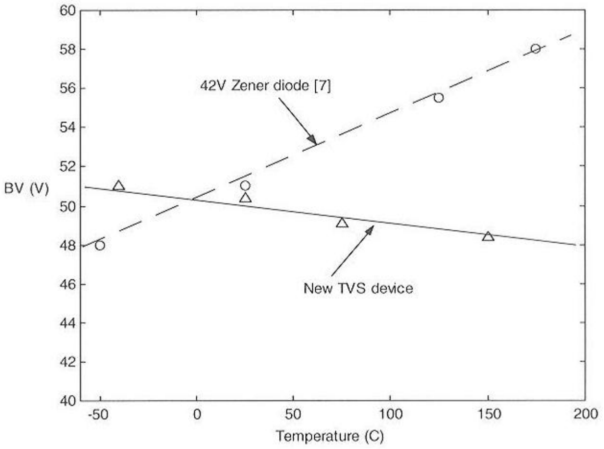

Fig. 7. Comparison in clamp voltages of the new TVS device and a 42-volt Zener diode as a function.

new TVS device offers a much smaller temperature variation in its clamp voltage than the conventional Zener diode

While these preliminary experimental results prove the concept of the new TVS device, there are still several issues, mainly related to the temperature dependence and energy capability of the TVS device, need to be resolved. The following discussions address these issues

5.1 Temperature Dependence of the Clamp Voltage

Due to the wide temperature range of the underhood automotive environment and the tight tolerance on the 42-volt bus voltage regulation, the clamp voltage of 42-volt TVS devices need to be relatively independent of temperature The clamp voltage of the TVS device V_{CLAMP} can be approximately given by

$$V_{CLAMP} = BV_{diode-string} + \sqrt{\frac{2I_{DS}}{K_P}} + V_{TH} \qquad (3)$$

where, $BV_{diode\text{-}string}$ is the breakdown voltage of the polysilicon *back-to-back* diode string, I_{DS} is the drain current of the MOSFET, K_p and V_{TH} are the transconductance and threshold voltage of the MOSFET respectively. Since the drain-gate diode string carries only a small amount of current, I_{DS} is also approximately the total current of the TVS device. For the reasons discussed in Section IV, $BV_{diode\text{-}string}$, which accounts for roughly 95% of the total clamp voltage, is essentially independent of temperature It well known that the threshold voltage of a MOSFET typically has a negative temperature coefficient while the transconductance of a MOSFET has a positive temperature coefficient. Depending on the drain current level and the MOSFET design, the total clamp voltage of the TVS device may demonstrate a slightly positive or negative, or zero temperature coefficient. As shown in Fig. 7, our prototype device shows a small negative temperature coefficient on its clamp voltage at 100 mA, decreasing from 51 to 48.4 volts when the temperature increases from -40°C to 150°C It should be pointed out that the threshold voltage, transconductance of the MOSFET as well as the breakdown voltage of the polysilicon diodes can all be adjusted to achieve the optimum temperature coefficient of the total clamp voltage

5.2 Energy Capability

Energy absorption capability of a TVS device is among the most important device parameters. For example, the load dump energy for the present 14-volt systems is typically specified at 50 joules [9] The energy specification for 42-volt automotive electrical systems depends on the selection of particular system configuration and control algorithm, among many design factors. It is uncertain how or if at all the automotive industry can specify a single value to cover all the candidate 42-volt system configurations, as in the case of 14-volt systems. Nevertheless, it is important to examine the limitation on energy capability of the proposed TVS concept and the design trade-off with other device parameters. We have investigated the issue both experimentally and theoretically

We have characterized commercially available 60-volt power MOSFETs with external drain-gate clamp diodes, using the previously described 14-volt load dump tester. The RC time constant of the 14-volt load dump tester was adjusted to approximately 4 milliseconds to match that of the advanced 42-volt power generation systems. The initial voltage of the capacitor at t=0 was varied to provide a variable discharging current. The MOSFETs were placed on a copper heating block so that the case temperature can be varied by a thermal controller Fig 8 shows the measured load dump energy capability as a function of the case temperature It is observed that the energy absorption capability of the clamped MOSFET decreases with increasing case temperature.

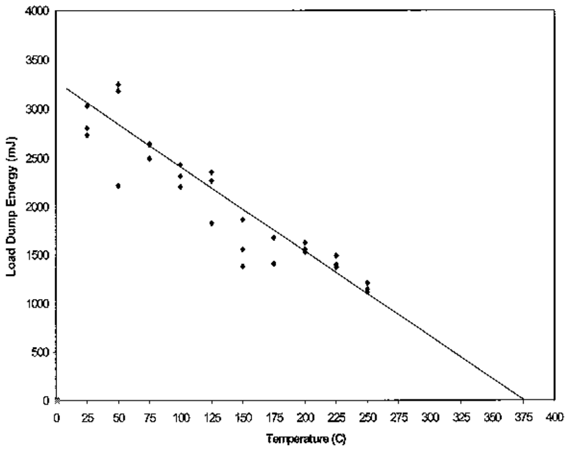

Fig 8 Measured load dump energy on 60-volt power MOSFETs with external Zener clamp diodes as a function of case temperature.

The energy capability of a clamped MOSFET is essentially limited by the actual peak junction temperature during a load dump transient. This is because at elevated junction temperatures semiconductor devices enter an "intrinsic" regime where both majority and minority carriers are generated and approach their "intrinsic" carrier concentrations due to thermal ionization. In this regime the resistance of a MOSFET decreases rapidly with increasing temperature because of the rapid generation of new carriers which more than offsets the decreasing mobility due to higher temperature If the temperature of any conducting area of the MOSFET exceeds the "intrinsic" temperature, device operation becomes unstable due to the negative coefficient of the device resistance Then a thermal runaway condition can exist where the reduction in resistivity causes the current constricted into the hot spot, which eventually reaches a very high temperature sufficient to destroy the device due to melting. Fig 8 indicates that the clamped MOSFET would fail if a peak junction temperature reaches a range between 370°C and 380°C.

It is very useful to estimate the energy capability limitation of the TVS device as function of die size, which will provide information on the cost-effectiveness of the concept The equation governing the heat transfer process in the TVS device is given by

$$\rho C\frac{\partial T(x,t)}{\partial t} = H(x,t) + \lambda\frac{\partial^2}{\partial x^2}T(x,t) \qquad (4)$$

where, $T(x, t)$ is the temperature at time t and location x on a one-dimensional axis, and $H(x, t)$ is the power density accounting for device heating due to carrier transport and recombination/generation ρ, C, and λ are the mass density, specific heat, thermal conductivity of silicon or copper (package), as listed in Table 2. The differential equation is solved numerically based on the following assumptions.

Table 2 Material properties for silicon and copper used in thermal analysis

Parameters	Silicon	Copper
ρ mass density (g/cc)	2 32	8 94
C specific heat (J/g/°C)	0 85	0.385
λ thermal conductivity (W/cm/°C)	1.5	3.91

A silicon chip with a total thickness of 300μm and a die size ranging from 0.1 to 0.4 cm^2 is used in the calculation The first 7μm of the silicon chip (measured from the top surface) is an epitaxial layer where nearly all the injected energy is dissipated originally The resistivity of this epitaxial layer can be adjusted to accommodate different levels of power density of the transient power pulse The rest of silicon chip is the substrate and simply serves as an electrical and thermal path as well as a thermal mass This structure represents a realistic approximation of a typical 60-volt power MOSFET structure

A 3000μm thick copper block with the same size as the silicon chip is used to model the lead frame (bottom contact piece) for a single-side package option An identical copper block is also used as the top contact piece for a double-side package option In reality, the copper pieces are always larger than the silicon chip that they accommodate. However, this factor is not accounted for in our simple one-dimensional analysis The solder layers joining the silicon chip with the copper pieces are also neglected in the analysis since they ordinarily have only a small contribution in the total thermal resistance The thermal resistance between the copper package and ambient for the electrothermal simulation is chosen to be 60 °C/W, which is typical for power semiconductor packages without using any heat sinks It has been found that this value does not have a significant impact on the final results unless a power pulse with an extremely long pulse width is applied to the simulated structure

A rectangular power pulse with a pulse width of 20μs is applied to the simulated TVS structure. The voltage of the input pulse is fixed at 58 volts. The current and power depend on the resistance of the simulated silicon chip We reduce the resistivity of the epitaxial silicon layer to increase the current and subsequently the power density of the transient power pulse until the maximum junction temperature exceeds 375°C, a critical temperature beyond which the device will fail This is based on our experimental results, as previously described We assume the ambient temperature is 25°C. Fig 9 shows the one-dimensional temperature distribution inside the silicon chip and copper package at various instants during the 20μs power pulse for a single-side package TVS with a die size of 0 2cm^2 and a current of 19.1A. It is observed that the maximum junction temperature rises rapidly during the power pulse and reaches 375 °C (or 648°K)

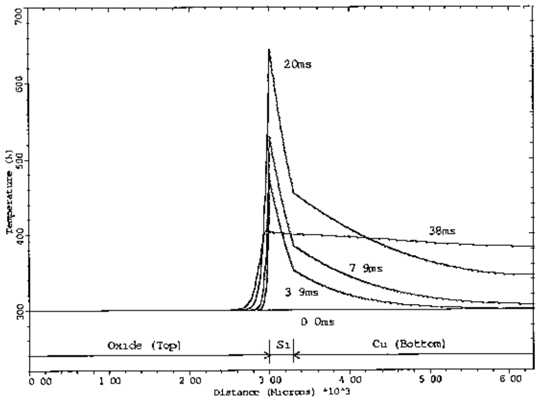

Fig 9 Calculated one-dimensional temperature distributions along the TVS device in a single-side package at various instants

at t=20 ms At t=30 ms, the peak junction temperature drops to 125 °C since the power source is cut off. The peak junction temperature occurs at the top surface of the TVS device The total energy absorbed during this period is approximately 22 3 joules Fig. 10 shows the one-dimensional temperature distribution for a double-side package TVS with a die size of 0.2cm^2 and a current of 48 9A The total energy absorbed during this period is approximately 56 7 joules, a 154% increase comparing to the single-side package case This is due to the fact that the heat is now removed from both sides of the silicon chip and the total thermal mass is also doubled. Fig 11 shows the theoretical limits on the energy capability of the TVS device (single- or double-side package) for a 20μs power pulse with a clamp voltage of 58 volts as a function of die size It provides qualitative information on the cost-effectiveness of the TVS concept However, it should be noted that the theoretical limit was calculated based on several idealized assumptions The actual energy capability of the TVS devices may be considerably lower than these theoretical values because of non-ideal factors For example, the solder layer that is not included in the calculation may have a major impact on the thermal performance, especially when voids exist in the solder layer

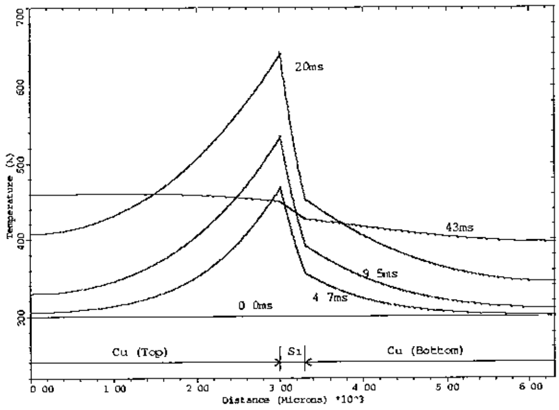

Fig 10 Calculated one-dimensional temperature distributions along the TVS device in a double-side package at various instants

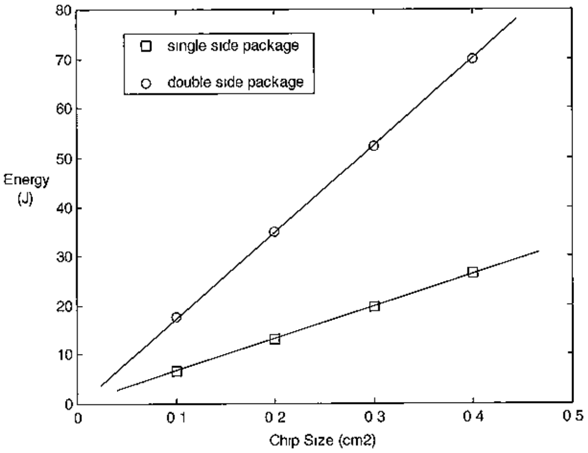

Fig 11 Theoretical limit on the energy capability of the TVS device as a function of chip size

6. Conclusion

In conclusion, we have examined the needs and options for passive TVS devices for load dump protection in 42-volt automotive electrical systems. The suitability and limitation of the commonly available automotive TVS devices, such as Zener diodes and MOVs, are carefully evaluated A new TVS device concept, based on power MOSFET and thin-film polycrystalline silicon back-to-back diode technology, is proposed to provide an accurately controlled clamp voltage and meet the new 42-volt specification Both experimental and modeling results are presented Issues related to the temperature dependence and energy absorbing capability of the new TVS device are discussed in detail. The proposed TVS concept, when combining with effective active control design, provides a promising cost-effective solution for protecting against load dump and other overvoltage transients in 42-volt systems

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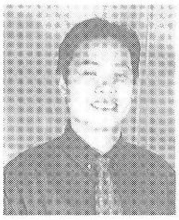

Dr. Z. John Shen received his B.S. in Electrical Engineering from Tsinghua University, Beijing, China in 1987, M.S. and Ph.D. degrees in Electrical Engineering from Rensselaer Polytechnic Institute, Troy, New York in 1991 and 1994, respectively. Between 1994 and 1999, he was with Motorola Inc. in Phoenix, Arizona, where he held the position of Senior Principal Staff Engineer in the Semiconductor Components Group. He joined the Department of Electrical and Computer Engineering and the Automotive System Engineering Interdisciplinary Program at the University of Michigan–Dearborn in 1999. Dr. Shen has been involved in developing advanced power electronic devices and circuits for automotive and industrial applications for over twelve years. His current research interests include automotive electronics, power electronics, modeling and characterization of power semiconductor devices, system reliability analysis, and automotive sensors and actuators. He has more than thirty journal and referred conference publications, and seven issued and numerous pending U.S. patents in these areas. He currently serves as the chair for the Technical Committee of Automotive Power Electronics of IEEE Power Electronics Society.