1200V Merged PIN Schottky Diode with Soft Recovery and Positive Temperature Coefficient

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Keywords

Discrete power devices, Devices, EMC/EMI, Semiconductor Devices

Abstract

Originally, the introduction of pn-junctions below the metal semiconductor interface of a Schottky diode was intended as a screening against high electric field strengths [1]. But the so called merged PIN Schottky (MPS) diode also provides a better trade-off between on-state voltage drop and turn-off losses as a consequence of lower junction voltage and reduced anode emitter efficiency [2, 3].

In 1992 International Rectifier Corp. introduced the first commercially available diode based on this concept [3]. The superior properties of those devices have been improved further by means of axial lifetime engineering [4-7]. The final result is an IGBT companion diode with low forward voltage drop, a positive temperature coefficient, soft reverse recovery, and high ruggedness. This paper shows the results of the new 1200V/75A device (active area: 48.6mm^2).

Introduction

Conventional PIN diodes using gold or platinum doping as a method of carrier lifetime control show major technological drawbacks [6]. On the other hand electron irradiation leads to a snappy recovery behaviour [6]. In general, a shorter over all carrier lifetime yields lower switching losses and higher ruggedness (because of lower peak power), while the forward voltage drop is higher and the reverse recovery tends to be more snappy. The root cause of this undesired trade off is the distribution of the electron-hole plasma within the device. If both the anode and the cathode are highly doped (i.e. show high emitter efficiency), then the plasma concentration is much higher on the anode side of the diode, due to the difference of electron and hole mobilities. If a device with such a plasma profile is commutated, the reverse current peak and thus the peak power will be high because of the high plasma level at the anode side. Afterwards, when the space charge region extends through the base of the diode, the reverse current will decrease rapidly due to the small amount of plasma. Furthermore, a premature snap off is more likely to happen. Therefore, a plasma profile with higher concentration on the cathode side and lower concentration on the anode side would be advantageous. Usually, this is called the inversion of the plasma profile.

The easiest way to achieve such an inverted profile is the use of a weak anode, i.e. an anode with low emitter efficiency, and a strong cathode. Unfortunately, the methods available to achieve a strong cathode are limited (band gap narrowing) or expensive (e.g. epitaxial material). Thus, the development trend during the 80’s went towards diodes with decreased anode emitter efficiency. Generally it is not sufficient to only reduce the doping of the anode, because this may introduce problems during blocking and under surge current conditions. The application of structured anodes can resolve these problems. The most popular concepts are the merged pin Schottky (MPS) diode [1, 2] and the self-adjusting p-emitter efficiency diode (SPEED) [8].

Apart from these device concepts a second trend came up, that is called axial lifetime engineering and that provides a plasma shaping based on the local variation of carrier lifetimes by means of heavy particle irradiation [4 - 7]. Although this is a very attractive method it did not find its way to the market in the 80’s and early 90’s because neither proton nor alpha particle irradiation was available on an industrial scale at that time [8]. Meanwhile, heavy particle irradiation technique reached a status that makes it suitable for volume production [6]. Therefore, it was decided to apply this method to MPS diodes in order to further improve the superior properties of these devices, i.e. to benefit from both concepts. A schematic of the resulting device structure is shown in Fig. 1.

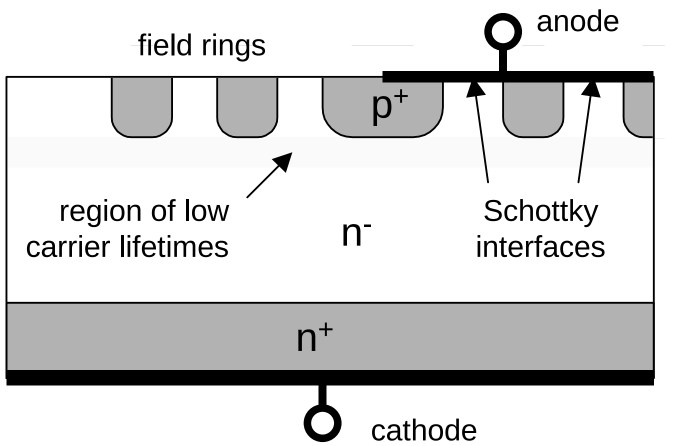

Fig. 1: Schematic of the new alpha irradiated MPS diode.

Design Considerations

It is well known that a diode has to be as thin as possible in order to obtain an advantageous trade-off curve between forward voltage drop and recovery losses [6]. On the other hand thinner diodes tend to show a more snappy recovery characteristic. This is supported by Figs 2 and 3 where the simulated reverse recovery behaviour of a 1200V/75A diode with homogeneous carrier lifetime is shown. The diode serves as a freewheeling diode of an ideal inductive load and is switched by an IGBT from 75A (nominal current) to a dc-link voltage of 600V (half of nominal blocking voltage). In Fig. 1 the resulting reverse current peak is plotted. Eq. 1 shows that the reverse current peak also determines the voltage drop $v_{L\sigma}$ (see also Fig. 2) across the stray inductance L_σ:

$$v_{L_\sigma} = -L_\sigma \cdot \frac{di_{Diode}}{dt} \quad (1)$$

In the closed loop this voltage has to be supported either by the IGBT or by the diode, because the DC-link was modelled by an ideal voltage source, which is usually in good agreement with reality. In other words, the difference between the voltage across the diode (plotted in Fig. 3) and the DC-link voltage minus the voltage across the IGBT (also plotted in Fig. 3) yields the voltage across the stray inductance (shaded areas in Fig. 3).

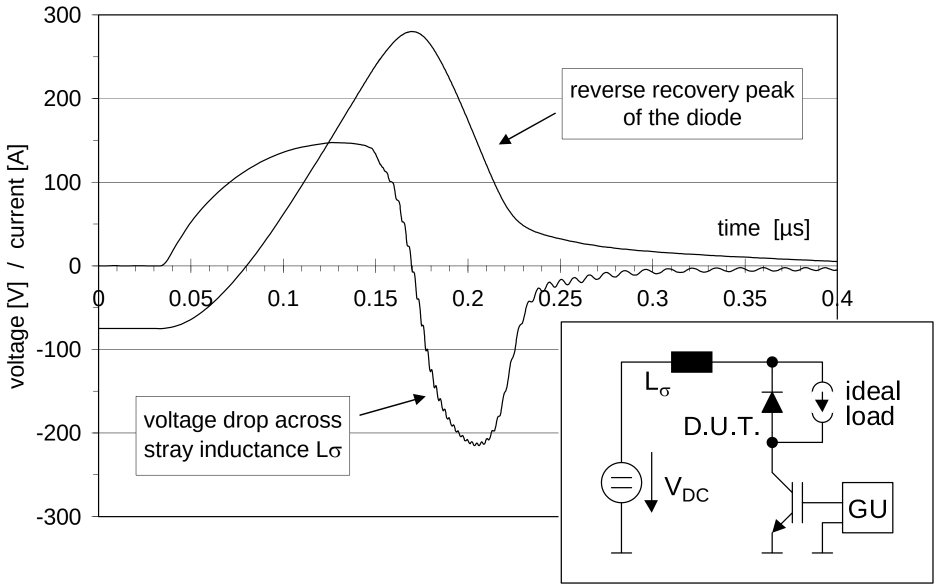

Fig. 2: Simulated switching characteristics of a diode, irradiated only with electrons (I = 75A,V_{DC} = 600V, di/dt = 5.4kA/µs, L_σ = 40nH). The voltage drop across the stray inductance L_σ proportional to the time derivative of the diode current.

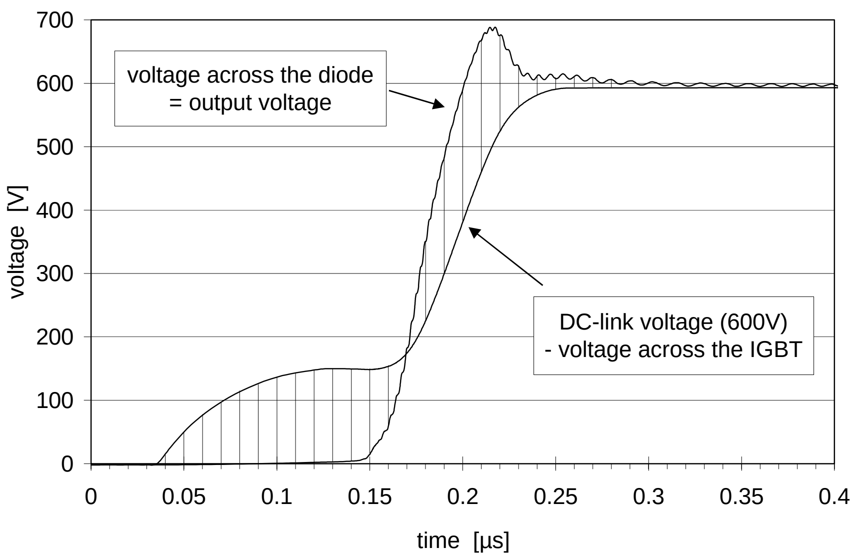

Fig. 3: Voltage across the diode (equals output voltage), and DC-link voltage minus voltage across the IGBT during the reverse recovery shown in Fig. 2. The shaded area represents the voltage across the stray inductance L_σ.

During the first phase of the reverse recovery while the diode is still conducting the IGBT supports the additional voltage, i.e. the IGBT supports a smaller fraction of the dc-link voltage. When the plasma close to the anode has been extracted, the diode starts to block. When the reverse recovery current peak reaches its maximum the di/dt becomes zero and the voltage across the stray inductance is zero also (Fig. 2). This is equivalent to the cross over point in Fig. 3. From that time on the additional inductive voltage is seen across the diode, because the voltage across the IGBT is determined by the gate unit. Thus, the voltage introduced by the stray inductance appears as an additional output voltage and leads to a steeper voltage rise across the diode compared to that across the IGBT. This is why active dv/dt control of an IGBT only addresses one source of the dv/dt. The other source is determined by the stray inductance and the second derivative (with respect to time) of the reverse recovery current. In particular, the output voltage is given by:

$$v_{out} = V_{DC-link} - v_{IGBT} - v_{L\sigma} \qquad (2)$$

and taking eq. 1 into account the output dv/dt by:

$$\frac{dv_{out}}{dt} = \frac{dv_{IGBT}}{dt} + L_{\sigma} \cdot \frac{d^2 i_{Diode}}{dt^2}. \qquad (3)$$

The dv/dt of the stray inductance adds onto the dv/dt of the IGBT. In the example (Fig. 2 and 3) the dv/dt of the IGBT is even smaller than that of the stray inductance!
Apart from the higher dv/dt the stray inductance also causes an overvoltage peak as shown in Fig.3. In cases where the di/dt is high, the overvoltage peak can exceed even the DC-link voltage.

In conclusion, these considerations yield two requirements for the shape of a reverse current peak. The first one is a small second derivative, i.e. a very round peak, to avoid high dv/dt, that would stress connected parts or would even make filtering necessary. The second requirement is a low di/dt at the falling slope of the reverse peak to avoid overvoltages. Unfortunately, a slow decrease of the reverse current would also lead to a bigger area below the current curve, i.e. higher losses. Therefore, the best compromise would be if the recovery tail phase begins at relatively high currents. Both requirements are met if the plasma profile is inverted as mentioned in the introduction.

In case of the existing MPS-rectifier the height of the reverse recovery peak had been adjusted to fit intended applications, by means of anode emitter efficiency control. Therefore, the plasma concentration at the anode side was already at the correct level, while the plasma concentration in the rest of the device had to be adjusted. In other words the electron irradiation bulk lifetime killing was reduced, in order to get a higher plasma concentration at the cathode side. This was compensated on the anode side by heavy particle irradiation. In particular, alpha particles were used to generate a low lifetime region in the n-base close to the pn-junction. The resulting diode characteristics are described in the following chapters.

Static characteristics

Due to the additional plasma at the cathode side of the new device the forward voltage drop of the new diode is substantially lower compared to a conventional MPS-diode with the same reverse current peak height (see Fig. 4). Furthermore, the new device shows a positive temperature coefficient of the forward voltage drop (important for paralleling) already at nominal current (75A), while the temperature coefficient of the conventional device only becomes positive above twice the nominal current. This advantageous behaviour is due to the influence of alpha particle irradiation, and is relatively insensitive to the irradiation dose as long as the dose exceeds a certain level. This shows that the lifetime in the region where irradiation creates damage is much shorter than in the rest of the device and that the exact value, as well as temperature dependencies does not matter as long as the lifetime is small enough. On the other hand the position of the low lifetime region influences the plasma shape and consequently the forward voltage drop as well as the shape of the reverse recovery current peak.

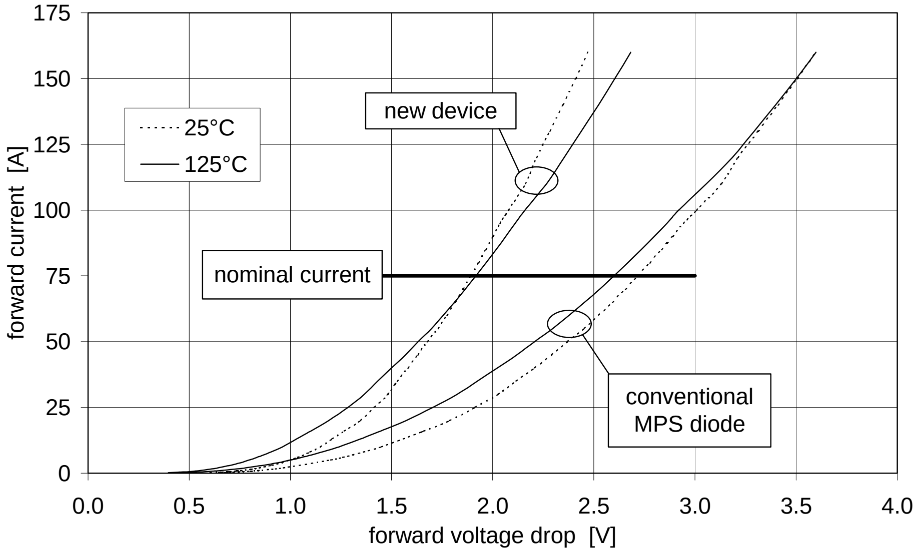

Fig. 4: Forward voltage drop of the new diode and a conventional MPS diode both measured at 25°C and 125°C

To ensure the blocking capability of the new device the proven field ring termination is employed (see Fig. 1), while the anode structure not just lowers emitter efficiency, but also screens the Schottky interface from high electric fields [3]. Therefore, the new irradiated device shows moderate leakage currents (even after alpha irradiation only 1-2mA at 1200V and 125°C) instead of the relatively high leakage common with ‘pure’ Schottky diodes.

Dynamic characteristics

Beside the on-state characteristics, the soft switching is the key feature of the new diode. Fig. 5 shows the comparison of the new alpha irradiated device with the conventional MPS diode under typical switching conditions, i.e. nominal current switched at half the nominal blocking voltage, high temperature, and moderate di/dt. As intended by the measures described above, the new diode shows a rounder reverse peak and, therefore, a lower maximum dv/dt. The superior shape of the reverse current peak also provides a lower di/dt at the falling slope and a tail that starts at a higher current level. Thus the overvoltage peak, shown by the conventional device is avoided with the new diode.

Looking at low currents and low temperature (Fig. 6), at which diodes tend to be more snappy, shows that the new device performs very well even under these challenging conditions. In particular, there is no ringing, no overvoltage peak, and a maximum dv/dt that is only half that of the conventional MPS diode.
Further reverse recovery parameters like maximum current peak, extracted charge, losses, and maximum dv/dt are shown in the appendix.

In addition to the soft switching the new diode demonstrates high ruggedness, i.e. no failure during switching at 125°C up to di/dt of 6kA/µs, current of 150A (twice nominal value), and DC-link voltage of 1200V, which is the nominal blocking voltage!

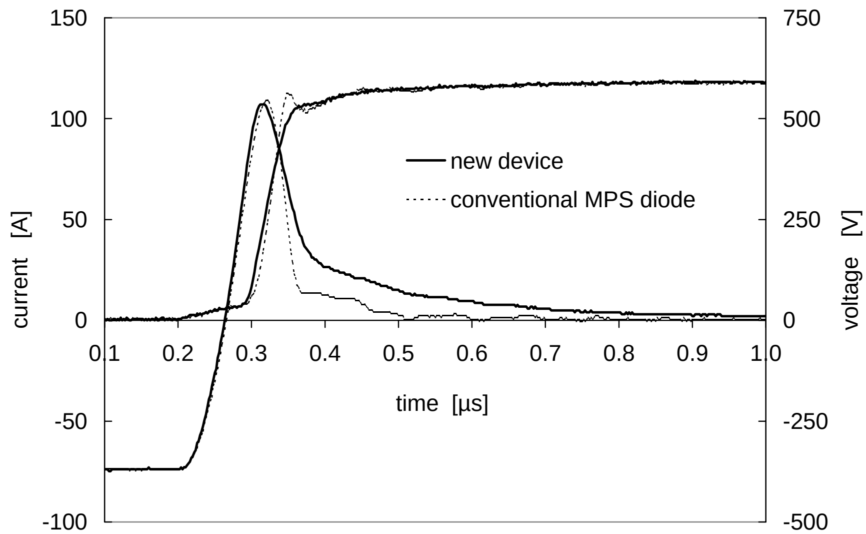

Fig. 5: Switching characteristics of the new diode and a conventional MPS diode at nominal current (75A), high temperature (125°C), and medium gate resistor of 10Ω (V_{DC} = 600V, L_σ = 50nH).

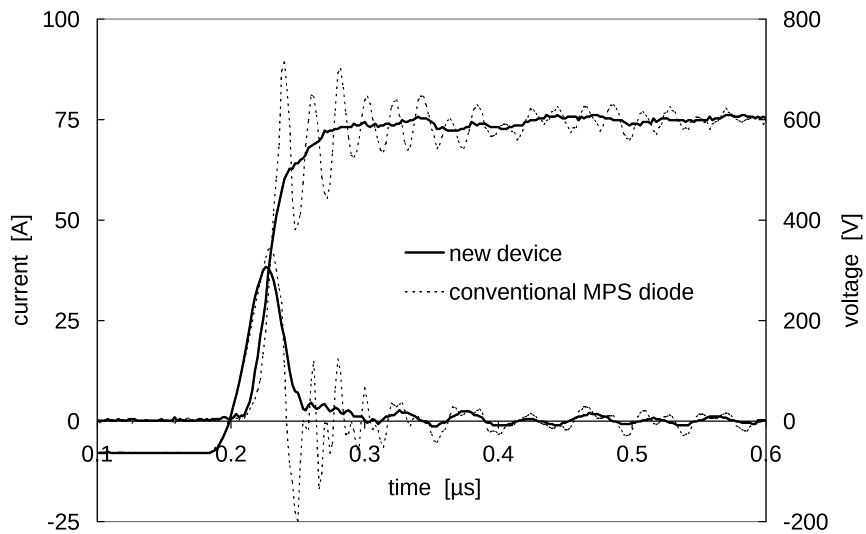

Fig. 6: Switching characteristics of the new diode and a conventional MPS diode at low current (8A ≈ $0.1 \cdot I_{nom}$), room temperature (25°C), and medium gate resistor of 10Ω (V_{DC} = 600V, L_σ = 50nH).

Conclusion

A new diode, which employs the MPS principle and axial lifetime engineering with heavy particles, has been demonstrated. The device shows low forward voltage drop with a positive temperature coefficient and soft recovery even under high di/dt conditions at low temperatures and low currents. Furthermore, the new diode is extremely rugged and is therefore, the logical answer to today's demands of fast switching without EMI problems.

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Appendix

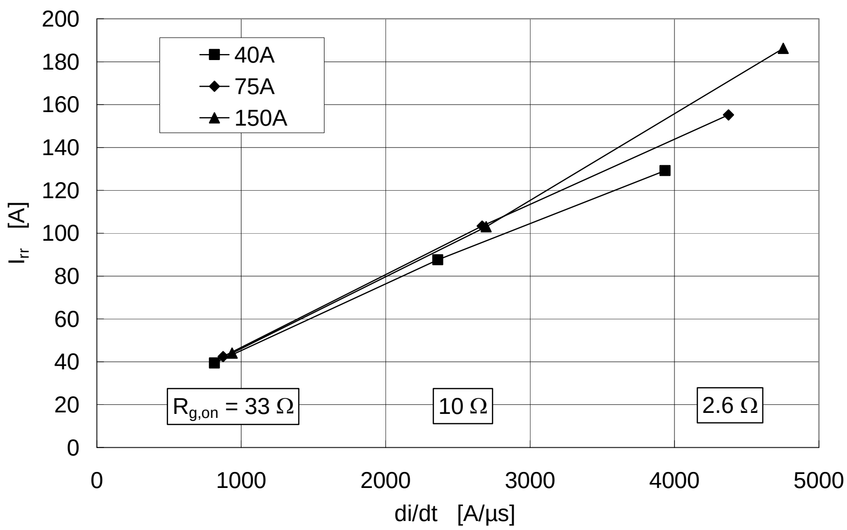

Fig. 7: Height I_{rr} of the reverse current peak versus di/dt at different currents (V_{DC} = 600V, T = 125°C, L_{σ} = 50nH).

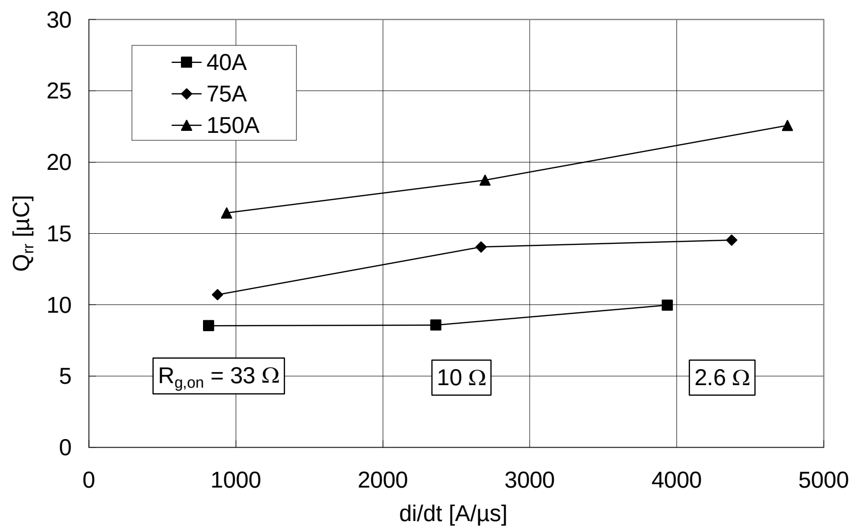

Fig. 8: Extracted charge Q_{rr} versus di/dt at different currents (V_{DC} = 600V, T = 125°C, L_σ = 50nH).

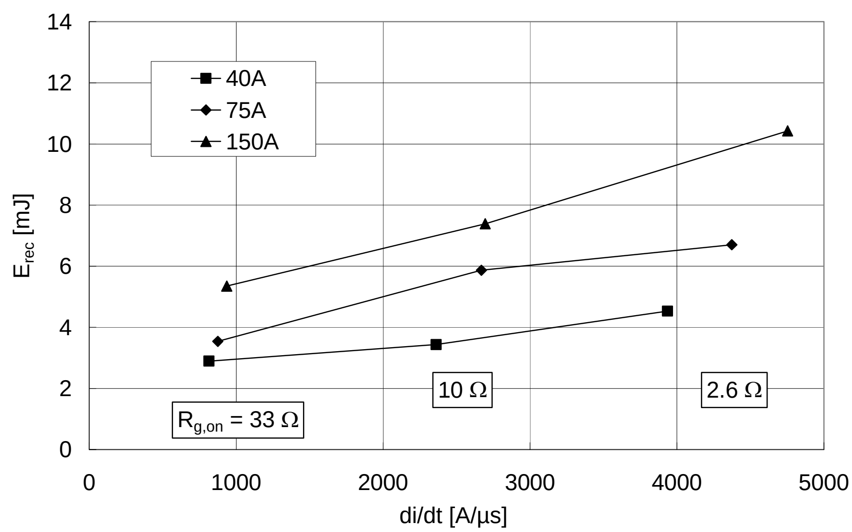

Fig. 9: Switching losses E_{rec} versus di/dt at different currents (V_{DC} = 600V, T = 125°C, L_σ = 50nH).

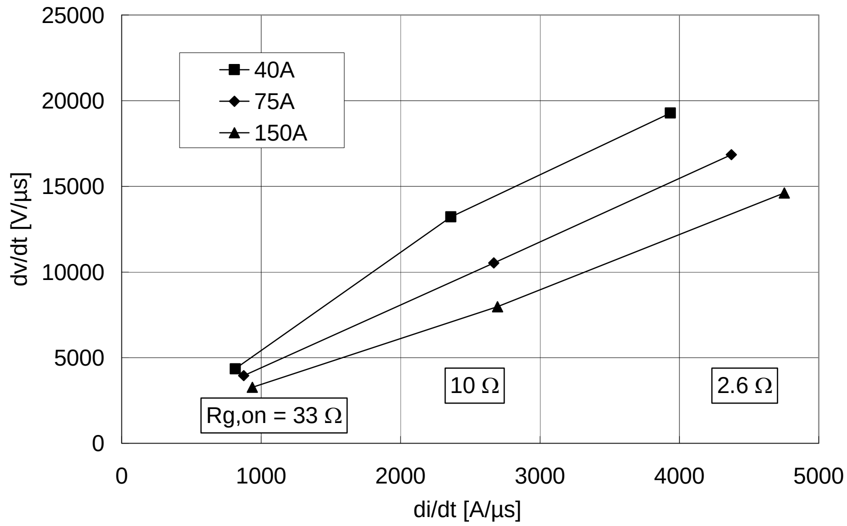

Fig. 10: Maximum dv/dt versus di/dt at different currents (V_{DC} = 600V, T = 125°C, L_{σ} = 50nH).