Final Report

1 Introduction

The solid state switch is the heart of todays power converters. Power converters have many applications, e.g. voltage supply for motors and transmission lines. Depending on the applications switching frequency and transformed power, the choice of switch changes from power MOSFETs for low power, high frequencies to Gate Turn-Off thyristors (GTOs) for high power and low frequencies. The criteria for the switch selection are minimal overall losses, built-in passive protection against extraordinary circuit conditions, long-term reliability issues, and, of course, the price of the switch.

The minimal overall losses for the switch are determined by the trade-off between the static (on-state) losses and the switching (mainly turn-off) losses, and is the issue mostly covered in this report.

The GTO has already been replaced to a great extent where the device blocking voltage is lower than 4500V by the planar IGBT. Replacements for the GTO for devices with higher blocking voltages have been sought in recent years, mainly because of the complex circuits needed to drive it, but also because the turn-off mechanism of the GTO used to be slightly different and more lossy than todays state of the art. Very recently, the hard-driven GTO, called GCT, changed the turn-off behavior of the GTO, which brought the turn-off losses down for this device, and therefore mainly the expensive driving circuit limits this device today.

One candidate for replacing the GTO thoroughly investigated today is the planar Insulated Gate Bipolar Transistor (IGBT), because of its reasonably simple fabrication technology, its built-in protection against short-circuit conditions and the simplicity of the circuits required to drive it. The disadvantage of the IGBT of today is that the conductivity modulation[1] is too low at the cathode side of the device, leading to an un-optimized sharing of the static (on-state) and switching losses in the device. The plasma levels at the boundaries are correlated to the injection efficiency of the present carrier type, i.e. electrons at the cathode and holes at the anode, and thus one may also refer to increasing the electron injection of the device.

The Trench-gated IGBT (TIGBT) allows for such an increase in injection efficiency, leading toward a plasma distribution comparable to GTO, however at the cost of a more complex, and thus more expensive, technology, as well as the loss of the forward-biased high voltage current saturation feature encountered in the IGBT; a feature that is used by circuit designers for short-circuit protection.

When allowing switching devices lacking built-in short circuit protection, MOS-gated thyristor structures (MGTs) become interesting because they provide a means of increasing the conductivity modulation at the cathode side (by adding an electron emitting junction) to the low-cost technology and simple drive circuitry of the IGBT, while not necessarily having a Short

[1] Conductivity modulation is the electron-hole plasma found in the weakly doped base regions during on-state of the solid-state power device. The level of the plasma determines the on-state voltage drop in the weakly doped regions.

Circuit Safe Operating Area (SCSOA) comparable to the IGBT. There is a large number of MGTs reported in the literature: EST, BRT, MCCT, MCT, FiBS, MGCT, IGTH, as well as related structures with slightly modified names. This work is aimed at evaluating the feasibility of a few of the reported MGTs for application in a 4000V, clamped inductive load switching environment, and to compare the properties of these devices to the planar and trench IGBT.

2 Turn-off of bipolar power devices

A bipolar device in the on-state has electrons and holes injected into it from opposite sides (called cathode and anode, respectively), supporting a conductive plasma in which the hole and electron concentrations are equal. The voltage in this bipolar region depends on the concentration of holes and electrons, i.e. the plasma level, but also on the ratio of electron current to hole current, because the electrons have a larger mobility than holes. Therefore, the on-state voltage will be lower for a device with a higher electron current density to total current density ratio, i.e. a higher electron injection efficiency at the cathode. The electron injection efficiency is reflected in the plasma level on the cathode side, which means that if the anode properties are kept constant, one may seek the optimal device by looking at the plasma level at the cathode side.

On the other hand, the on-state plasma distribution determines the turn-off losses of the device. In this work, an analytical model taking into account the important physics during the voltage-rise period of inductive switching was developed, to analyze how the on-state plasma affects the turn-off losses. The model calculates the time-dependent voltage rise for an inductively switched bipolar device, with the electron injection interrupted at $t = 0$. The obtained expression is compared to simulation at two different current densities in figure 1 (a), and as it can be seen, the agreement is acceptable. In figure 1 (b), the analytical model is applied to two different on-state plasma distributions, with exactly the same charge content, representing devices with good and bad electron emitters. According to the model, the plasma distribution corresponding to a good electron emitter generates less losses at every time-point than a bad electron emitter, shown in figure 1 (b). The time after the clamping voltage is reached, is not treated here, i.e. the commutation of the current to the diode and the tail-current-phase of the IGBT. It can be said, however, that the remaining plasma after the clamping voltage is reached will determine the length and the magnitude of the current tail, and that the device reaching the clamping voltage first will have more stored charge, i.e. that the bad electron emitter is worse also in this sense.

For devices without complete control of the electron emission, e.g. BRT, electrons may continue to be injected during the voltage rise. The effect of injected electrons at the cathode causes deviation from the ideal behavior presented above. In the presence of avalanche-generated charge, electrons will also be introduced close to the cathode contact. Such injected electrons slow down the voltage rate of rise, and in the limit, one or both of these two processes slows down the voltage rise to zero, thus arriving at a new stationary condition without having turned the device off – leading to malfunction of the circuit or device destruction in the worst case. The limit is called the Reverse-Bias Safe Operating Area (RBSOA). In general, when switching at voltages well below the devices static blocking voltage, the RBSOA is determined by latch-up of parasitic or main thyristors, and at switching voltages closer to the voltage rating, dynamic avalanche limits the device.

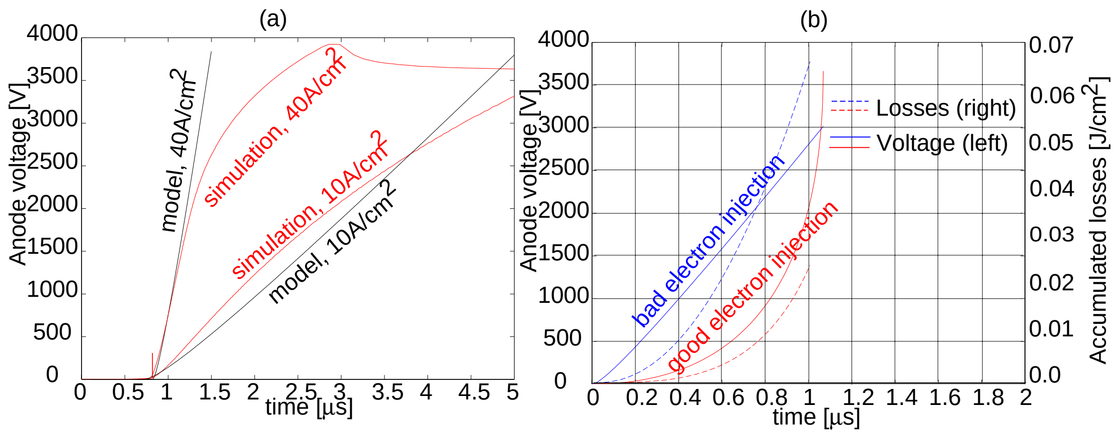

Figure 1: (a) $V(t)$ traces from the analytical model and from turn-off simulations of 10 and 40A/cm^2 vs 3600V. (b) The traces of the analytical model applied to two on-state plasma distributions with the same total charge content.

3 Insulated Gate Bipolar Transistor — IGBT

The IGBT was presented in the 1980's, combining the low turn-off loss and easy control of the power MOSFET with the low on-state voltage associated with bipolar devices. The features of the IGBT are the high input impedance (voltage control), stable operation during turn-off due to the MOS control over the electron injection and the possibility for high voltage current saturation. The IGBT is available on the market today for blocking voltages up to 4500V; an IGBT with more than 6000V blocking voltage is expected in the near future, and the most severe disadvantage of the IGBT in this voltage range is the high on-state voltage compared to thyristors, due to too low electron injection of the n-channel MOSFETs.

All modern power devices gain from the advantage of minimizing the emitter efficiency of the anode, i.e. minimizing the hole current to total current ratio in the device. The transparent emitter concept can be applied to any kind of device with the switching control on the cathode side, and without reverse blocking capability. In recent years, local lifetime control by heavy-particle irradiation has entered the power device scene, which makes it possible to optimize the plasma distribution in the power device, and to further minimize the anode emitter efficiency.

Planar technology Todays state of the art IGBTs for high voltage (more than 2500V blocking voltage) application are made with a double p diffusion as is outlined in figure 2 (a). The width of the IGBT cell is wide, above 50μm, the channel length approximately 4μm, and the deep p-base to n$^-$-base junction approximately 8μm. The wide cell-pitch is utilized for two reasons; firstly to minimize the JFET effect, and secondly, to lower the channel density in order to obtain a low saturation current density. Double p-layers have been used in planar technology to provide a compromise between the threshold voltage (the channel doping) and sensibility to latch-up of the parasitic thyristor formed between the n$^+$-source and the anode p$^+$-emitter (sheet resistance of the combined p-layers). The state-of-the art IGBT has a maximal p-type doping below the n$^+$-source under the condition that the maximum p-concentration in the channel may not exceed approximately $2\times10^{17}\mathrm{cm}^{-3}$, corresponding to a threshold voltage around 7V for a 0.1μm thick gate oxide.

The JFET effect lowers the electron injection from the n-channel MOSFET. The reason for this consists of a geometrical part and a part which has to do with the effect of holes in the vicinity of the channel. For the technology used in this work, the trade-off between the JFET effect and the channel density leads to a minimal on-state voltage at a cell-pitch of 70μm, however, to increase the saturation current density, smaller cell-pitches (50–58μm) have been used.

The IGBT has excellent switching properties due to the simple control of the electron injection by the n-channel MOSFET. During the work in this project, successful turn-off simulations have been carried out up to 175A/cm^2 versus 4000V, corresponding to a switched power of 700kW/cm^2, which is beyond what is feasible in a real device. At high current densities the parasitic thyristor formed between the n$^+$-source and the p$^+$-emitter may latch, which limits the current handling capability. Even though this was not an issue during the simulations carried out during this work, it is a well-known problem for real devices.

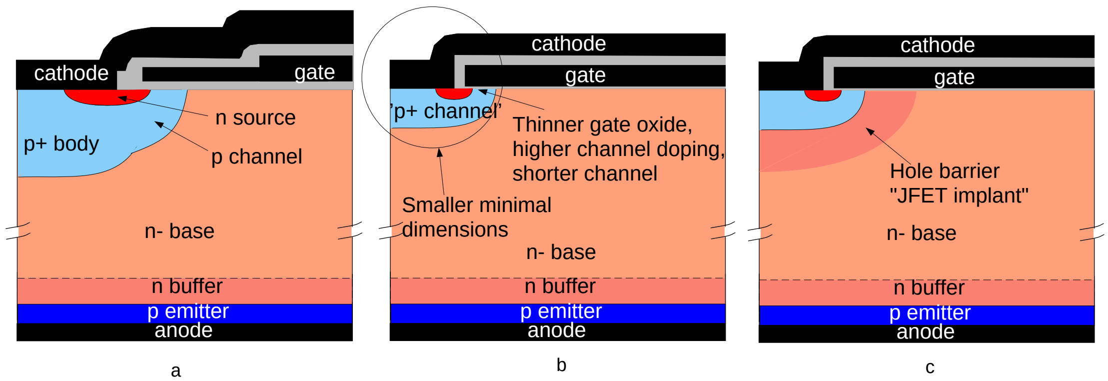

Figure 2: Draft of today's planar IGBT to the left (a). In the middle (b), a possible candidate for the next generation planar IGBTs with minimized cells. To the right (c), an IGBT cell with an added JFET implant is drafted, which improves the forward characteristics of (a) and (b), but might give problems with cosmic-ray stability.

Trench technology The rapidly increasing on-state voltage of IGBTs with larger blocking voltage has led to the development of the trench-gated IGBT. By aligning the MOS-channels in the IGBT vertically (see figure 3), several mechanisms help to increase the electron injection at the cathode.

1. The JFET effect is eliminated, reversed or reduced, depending on how one defines it. Since there is no interaction between adjacent p-collector regions in the TIGBT, the intuitive interpretation of the JFET effect from the planar IGBT is lost, and thus the TIGBT might be better understood without this conception.

2. The geometry of the TIGBT forces the holes to crowd together upon collection whereby the plasma level is increased.

3. The sides and bottoms of the trenches extend the inversion layer length and facilitate electron injection from around the entire trench — the inversion / accumulation layer could be said to act as the n$^+$-emitter of a thyristor.

4. The hole current along the n-MOS channel will bias the MOSFET and increase the electron current, and this phenomenon is accentuated in the TIGBT due to the geometry of the trenches in the flow-direction of the holes.

The combination of these effects lead to a thyristor-like plasma distribution in the TIGBT, however, it is difficult to distinguish the effects of these mechanisms separately. The following influences of the design on the on-state can observed:

- The depth of the trench is to be made as large as possible. The technology limits the trench depth.
- The distance between the trench gates is to be minimized, limited by the critical dimensions of the technology.
- Trench width is to be maximized, at least within the limits of todays feasible technology, limited by the ability to fill the trenches with oxide and polysilicon gate material.
- The channel quality is especially difficult to maintain due to the trench etching process, and it has a large influence on the on-state properties.

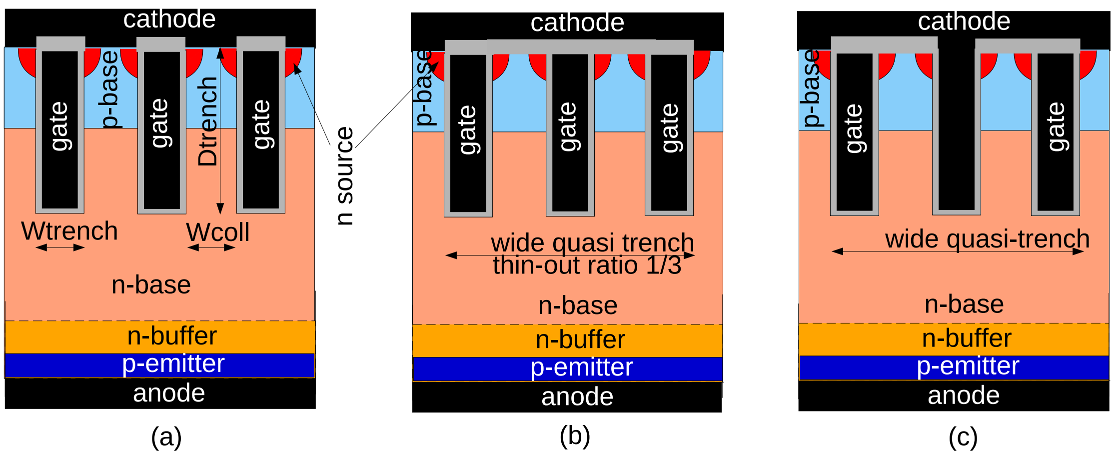

Figure 3: Development of the trench IGBT structure. (a) The conventional structure with every trench contacted to the cathode. (b) IEGT concept, with a fraction of the collector fingers connected to the cathode. (c) Improved IEGT structure with radically decreased Gate-collector capacitance by connecting unused trench electrodes to the cathode metal.

In this work, a conventional TIGBT has been simulated with a trench-depth of 8μm, and with a trench-width of 3μm. The TIGBT gets better with larger widths and depths of the trenches, but the values chosen are definitely feasible for a real device. The TIGBT, as the IGBT, was able to switch more 500A/cm^2 without parasitic latch-up or failure due to dynamic avalanche.

4 MOS-controlled thyristor structures

In this work, six different MOS-controlled thyristor structures were investigated using simulation, namely the Emitter Switched Thyristor (EST), Base Resistance controlled Thyristor (BRT), Dual-Gate MOS-Controlled Thyristor (DGMCT), Dual MOS-Gated Control Thyristor (DMGCT), Base-Coupled Insulated Gate THyristor (BCIGTH) and the Filamentation-insensitive Bipolar Switch (FiBS). There are numerous other structures reported in the literature, but these five structures are representative for the different concepts applicable to the other structures.

The EST has been given a lot of attention, and a few different variants of the fundamental structure have been proposed. The operation principles does not differ from the MCCT and ITT. The turn-off off the EST is very IGBT-like, i.e. the electron current from the cathode is completely controlled by a MOSFET, leading to a stable turn-off behavior. The most severe disadvantage for the EST is the forward characteristics at low current densities. Well-known is that the EST has a lower voltage drop than the rest of the thyristor-based devices, and at low forward current densities the EST exhibits an pronounced snap-back. As the DC-link voltage is increased, the current density has to be decreased to constrain the switching power, and therefore the bad forward properties of the EST at low current densities play a larger role for higher voltages. The conclusion is that the EST simply does not show a large enough improvement over the IGBT to be interesting at 4000V DC-link voltage, although the switching of the EST is stable and reliable.

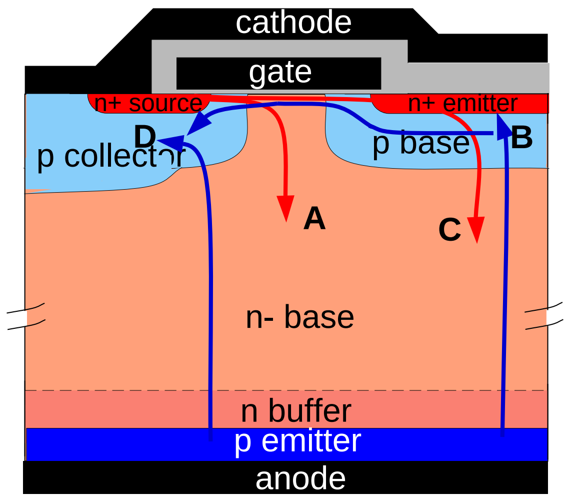

Figure 4: The geometry and operation principles of the EST cell. The n^+-emitter is connected dynamically to the cathode via the n MOS channel, which ensures a safe turn-off. Unfortunately, it also causes an extra voltage drop due to the channel resistance in on-state.

The BRT is developed from the basic MCT structure, and is a true thyristor without a series MOSFET resistance. Therefore, the BRT has a great potential for low on-state voltage. For turn-off, the BRT relies on the efficiency of p-channel MOSFETs to break the latched thyristor state, which raises questions about the stability of turn-off. As in the case with MCT, problems arise when many single devices are switched in parallel, because of small process-induced variations between the cells cause un-even current sharing of the cells, so-called current filamentation. During this work, turn-off simulations of two BRT structures with varied thyristor properties were carried out. By using an accentuated thyristor design, the on-state properties can be improved at the cost of worse turn-off performance. Therefore, also a weak integrated thyristor was simulated to establish if stable turn-off could be achieved. In figure 5, the output from simulations of the weak thyristor is shown, and it can be seen that even this design has problems turning off electron current before the clamping voltage is reached, in a 75A/cm^2 turn-off simulation. Needless to say, the better thyristor structure shows worse turn-off capability, and fails completely to turn 50A/cm^2 off versus 4000V. During this work, no structure could be achieved which showed better properties than the IGBT even at lower current densities.

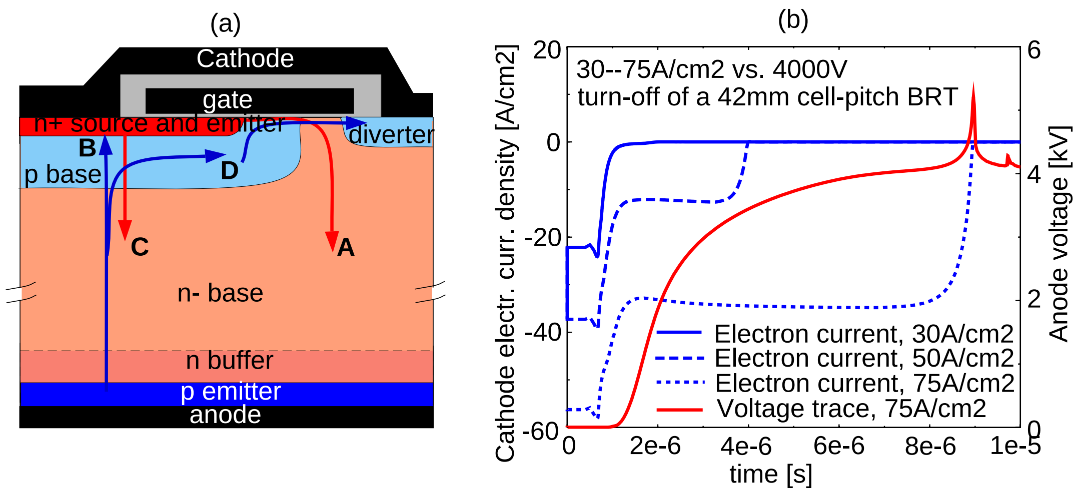

Figure 5: (a) The operation principles of the BRT. Electron injection is initiated by the gate (A), which turns the thyristor on (B-C). At turn-off, the gate voltage is reversed, and the hole current is transported through the MOS channel below the gate and out through the diverter (D).

The DMGCT is a further development of the EST principle, i.e. to let the emitter current flow through a series MOSFET before entering the integrated thyristor. The main difference is that a p-channel MOSFET is utilized, and thereby a Floating Ohmic Contact (FOC) has to be used to transform the hole current into electron current. The concept allows for minimal diversion of the p-base hole current in the thyristor as well as minimal channel lengths for the series MOSFET, and therefore the DMGCT has a better on-state voltage than the EST. Since the emitter current is completely controlled by the gate bias, the DMGCT inherits the stable turn-off operation of the EST, and it also has to be noted that no parasitic thyristor is integrated in the design. The price that has to be paid for these features is the introduction of the FOC, i.e. a second metal layer which has to be isolated from the cathode, which adds extra process steps and raises the production costs. In this work, simulations up to 100A/cm^2 were carried out without any parasitic electron injection. One problem that was observed, however, is a very sharp electric field peak at the gate oxide – silicon substrate interface of the p-channel MOSFET during the discharging of the device, due to a combination of a positive gate bias during turn-off and the large amount of holes coming from the on-state plasma. This pathological might cause gate reliability issues in a real device although the only consequence during simulation was a very small amount of avalanche generated charge in the silicon substrate.

The BCIGTH is a variant of the IGTH, which is in turn does not differ in principle to the BRT. The BCIGTH has a unique turn-on mechanism making it turn on at a certain collector–emitter voltage rather than at a certain current. Therefore, it lacks the the high latching and holding current of the BRT. The snap-back is still there, but with almost zero current, which makes the device easier to turn-on in parallel. Since the turn-off mechanism does not differ in principle from the BRT, the same bad maximum controllable current is expected in this case as well. In figure 6 (b), the failure to turn-off electron current already at 50A/cm^2 is displayed. At 75A/cm^2

the device fails to turn off. The price for better turn-on properties is paid by the introduction of a metal strap which, as in the case of the DMGCT, raises the production costs of the device. The nice turn-on, however, does not justify the bad turn-off capability of the BCIGTH.

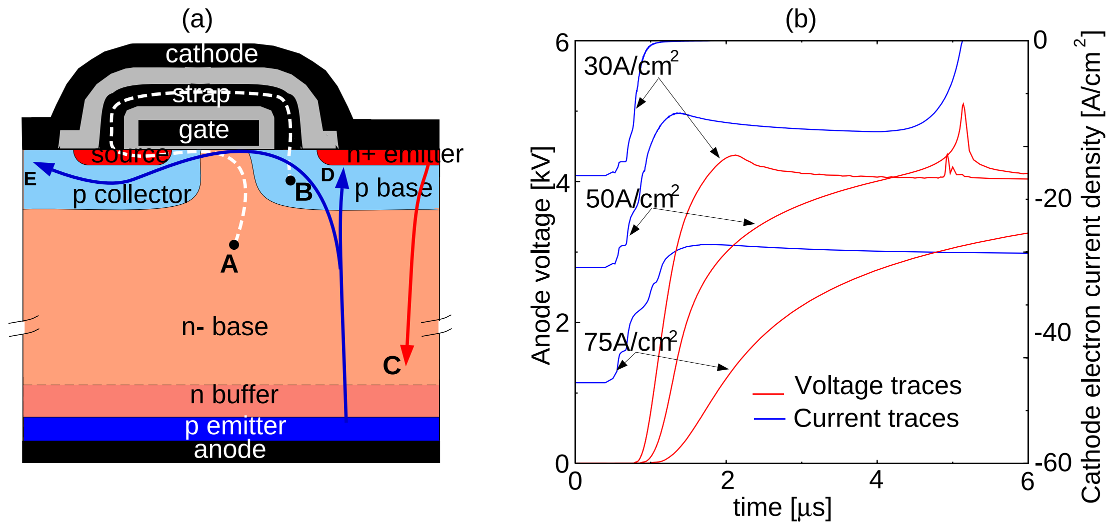

Figure 6: (a) The structure and operation principles of the BCIGTH. The potential in the p-base (B) is coupled via the n MOS channel to the n^--base potential (A), which triggers the thyristor at a certain voltage rather than at a certain current. (b) Failure for the BCIGTH to turn off electron current when turning off 50 and 75A/cm^2.

The FiBS was introduced in 1991, to overcome problems with current filamentation associated with MOS-gated thyristor structures. In figure 7 the geometry and operation principles of the FiBS are displayed. The complex doping design of the cathode makes it necessary to employ epitaxial growth of silicon as one process-step, which is very expensive. The FiBS operates according to the same principles as the EST, but has a series of advantages over its ancestor. Firstly, the n^+-source is isolated and thus no parasitic latch-up can occur. Secondly, the p-base has no static connection to the cathode, and thus the entire hole current makes up the base current for the upper npn transistor of the thyristor, and thus the on-state is very low compared to the EST. Thirdly, the n-channel MOSFETs feeding the n^+-emitter can be more densely packed which also improves the on-state. The result is that the FiBS actually shows the best on-state voltage of all investigated devices for the low current densities applicable for switching at 4000V.

The FiBS can be driven with one or two gate signals, i.e. with or without possibility for high voltage current saturation. In this investigation, only one gate signal was used, and the FiBS has proved to turn off 125A/cm^2 versus 4000V without parasitic electron injection. Of course, switching 500kW/cm^2 will cause significant dynamic avalanche and possibly cause turn-off failure, but this effect is present in all power devices – the intrinsic turn-off ruggedness of the FiBS is excellent.

DGMCT is a variant of the conventional MCT, which was the first reported MOS-controlled thyristor. The difference is the possibility for high voltage current saturation by the operation of a second gate. The geometry and operation principles of the DGMCT are displayed in figure

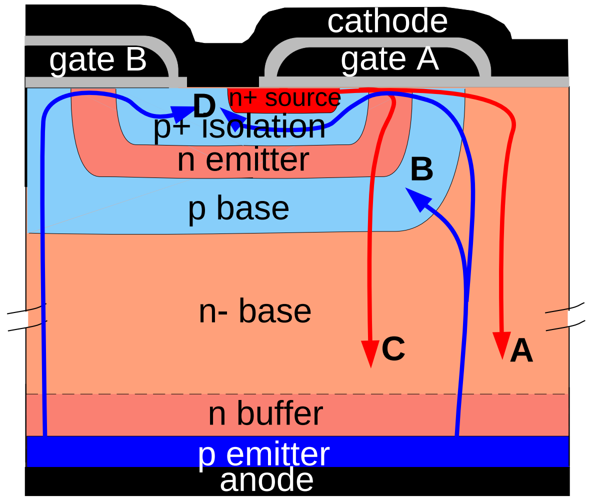

Figure 7: The structure and operation principles of the FiBS. FiBS is operated in the same manner as the EST, except for the introduction of a second gate, which may be controlled independently, and the removal of the parasitic thyristor.

8 (a). The operation principles does not differ much from the BRT, but the more complex cathode doping design isolates the p-base from the cathode contact. This is the reason why a true thyristor on-state can be obtained with the MCT. At turn-off, however, the MCT relies on the p-channel MOSFET to discharge the p-base and break the latched thyristor state, giving the MCT a low maximum controllable current as in the case of the BRT and the BCIGTH. The structure simulated has the best forward properties of all investigated structures at high current densities, and almost the best at lower current densities, but the maximum controllable current is too low. Simulations show that the DGMCT fails to turn-off the electron current at 75A/cm^2. For the DGMCT, an experiment with 20 parallel cells was conducted at 15A/cm^2. One of the cells had a slightly perturbed n$^+$-emitter, and the current sharing of the cells were studied. In figure 8 (b), the onset of current filamentation is shown when turning off only 15A/cm^2.

5 Conclusion

The forward characteristics of all simulated devices are displayed in figure 9. The lifetime chosen for comparison was 8μs for electrons and 2μs for holes, and the gate voltages were ±15V, where applicable. The current range is chosen to less than 200A/cm^2, since no device would survive switching higher currents against 4000V. At such low current level, any eventual high voltage current saturation does not show with the given gate voltages, but the possibility for this feature exists for most of the devices. Since the anode properties have been kept constant for all devices, the on-state voltages will be entirely determined by the cathode properties. As can be seen, the FiBS shows the best on-state voltage below 200A/cm^2, which is somewhat surprising due to the series MOSFET inherent in the FiBS design. It can be explained by the high density of n-channels supplying electrons to the n$^+$-emitter, and the fact that the thyristor is completely un-shorted in the on-state. As the current density increases, the devices with no series MOSFET in the design will have a far better on-state voltage than the others.

In figure 10, the on-state voltage is mapped to the x-axis and the corresponding turn-off energy is plotted on the y-axis for all the devices simulated. The trade-off curves where gen-

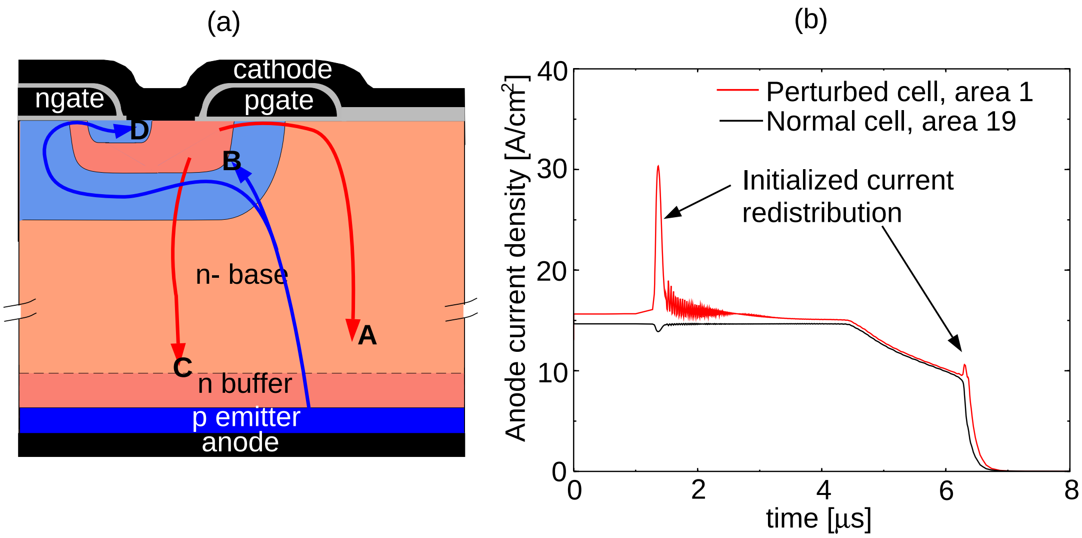

Figure 8: (a) The DGMCT structure and its operation principles. The DGMCT is operated in a manner similar to the BRT, but the static diverter is placed within the n^+-emitter. The two gates cannot be operated with the same gate signal. (b) On-set of current redistribution in an experiment with 19 normal and 1 perturbed cell. The experiment was to turn off 15A/cm^2 versus 4000V.

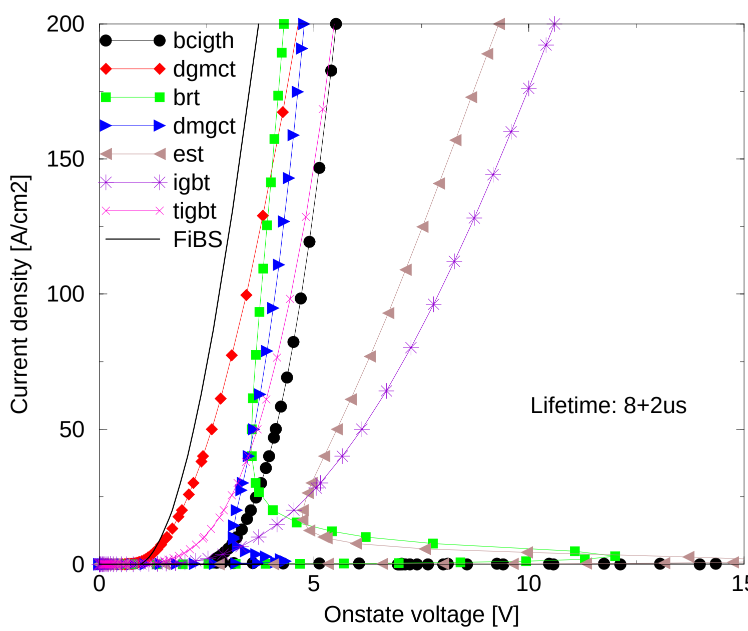

Figure 9: A comparison of the on-state voltages of all simulated structures. It can be noted that even though the FiBS has a series MOSFET resistance, the forward characteristics of this device is the best below 200A/cm^2. At higher current densities, however, the pure thyristor devices will be better.

erated by varying the homogeneous lifetime[2] between[3] $4 + 1\mu$s and $12 + 3\mu$s. The turned off current density at the comparison was 30A/cm^2, which is a feasible normal mode of operation when switching against 4000V. A device is judged after how closed to the zero point its curve comes in this trade-off, since this suggests the lowest overall losses. In most cases, the trade-off relationship can be guessed from the on-state voltage at 30A/cm^2 from figure 9, with the exception of the BRT, which shows the worst trade-off relation even though the on-state voltage at 30A/cm^2 is lower than at least the IGBT. The reason for this is the failure to turn-off the electron current before the clamping voltage is reached, which can be seen in figure 5. As the device does not turn off like an IGBT, the trade-off relation is worse than predicted by the on-state voltage.

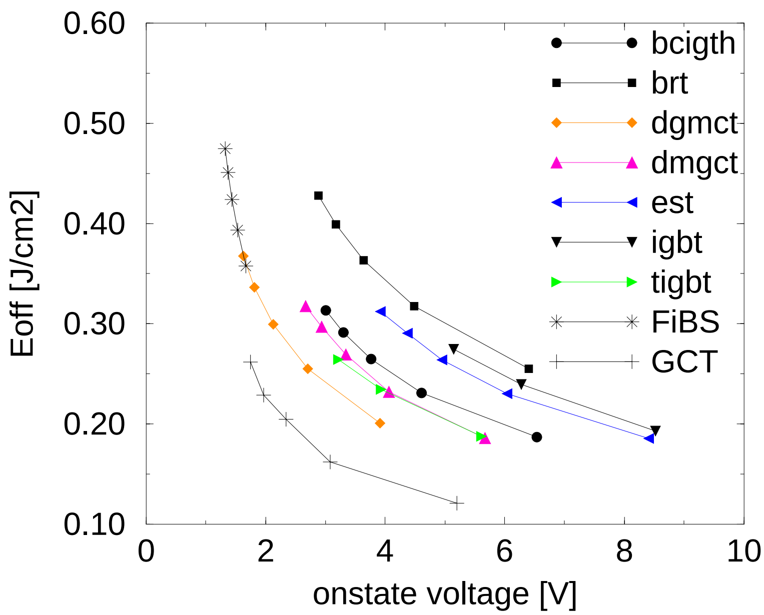

Figure 10: The trade-off between on-state voltage and turn-off losses of the simulated devices.

If all devices would have the same technology, and the same SOA, the choice of device would be the simple task of choosing the one with the lowest on-state at the anticipated current level, for which the reason is explained in section 2.

As it has been shown, the MCT-type devices simulated (BRT, DG-MCT and BC-IGTH) have a low MCC and are unreliable when switched in parallel, which puts a question-mark in front of the applicability of these in 4000V inductive switching. Of course, a circuit designer could determine that his circuit provides switching conditions within such limits that ruggedness for extraordinary conditions does not play a role. In that case, the devices with difficulties turning off less than twice the prospected current might be a good option. Since such circuits are rarely encountered, the more robust devices will take the largest part of the market.

The EST-type devices simulated (EST, FiBS and DMGCT) have shown to be robust to the point where dynamic avalanche and associated self-heating of the silicon limit the device, i.e. at power density levels around 400kW/cm^2.

The EST is easily fabricated with its IGBT-like process, which should make it a competitor to the IGBT. Among the disadvantages, the forward snap-back, and the questionable on-state

[2]The numbers are to be understood as the electron + hole lifetime, the sum being the high-injection level lifetime

[3]The lifetime for the FiBS was varied between $10 + 2.5\mu$s and $16 + 4\mu$s.

advantages over the IGBT at low current densities should be noted. The EST is a competitor to the IGBT for lower voltages, since the current density is allowed to increase and the thyristor integrated into the EST can be fully latched.

The FiBS has excellent intrinsic characteristics, with a reservation for a possible snap-back in the forward characteristics for low lifetimes. This device, however, is associated with an expensive and complex fabrication technology involving epitaxial growth of silicon and a 5 layer cathode doping structure, and the task of comparing the extra cost of such a process to the overall gain in device performance is beyond the scope of this work.

The DMGCT, finally, is associated with relatively simple fabrication technology, differing from the IGBT process only in the introduction of a second metal layer. The low on-state voltage and the stable turn-off make the concept interesting for experiments. The forward characteristics show a minor snap-back, which might be possible to remove by redesigning the device. The extra metal layer and the necessary oxide layer could become a packaging issue since the thermal resistance of the cathode is increased or the degrees of freedom for bonding or soldering will decrease.

The IGBT is possibly seeing its 3^{rd} generation in a near future, which would increase the forward characteristics and decrease the ruggedness of the device. Since the fabrication technology is simple and the performance is stable, the IGBT will surely take a piece of the market at elevated voltages in the future, especially for high switching frequencies.

Trench IGBTs are shown to greatly improve the properties of the planar IGBT, limited only by the quality of the fabrication process. The IEGT concept bypasses the problem of producing wide trenches, but the expensive fabrication process limits the use of the TIGBT to applications where its properties are especially asked for.

It has been shown in this work that there are possible improvements to be made to the planar IGBT which lower the overall losses, either by changing the structure of the IGBT itself, or by utilizing a different device concept. This work has lead to further investigation and development of new IGBT concepts mentioned in this report, and to the decision *not* to develop MOS-controlled thyristor structures for use in high-voltage applications. A smaller energy dissipation in the switch naturally leads to an improved dissipated energy to converted energy ratio. Today, actually the trend in the converter manufacturing industry is that this loss-reduction is mainly sacrificed in order to improve the converter functionality. An effect is that it is possible to increase the switching frequency and thereby improve the quality of the electrical energy after conversion, which may lead to lower energy losses in later stages. Another effect is that the converter can be made more compact, light-weight and reliable. In a locomotive, new technology can reduce the mass of the locomotive by several tons, resulting in huge lifetime energy savings. With further development of the switches, a point will be reached where improved energy-efficiency of the converters is made the main target for the converter users and manufacturers.