Simple Power IC

for the

Switched Current Power Converter:

Its Fabrication and

Other Applications

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Introduction:

A simple power integrated circuit (power IC) is optimized for high performance and economical manufacture. The premise is that a simple power IC can be made using the fabrication steps of a DMOS MOSFET if all of the MOSFETs in the IC are the same except for their active area. Some of the MOSFETs must be isolated, and they must be interconnected and terminated, but no other extra layers or diffusions are used.

One application for the simple power IC is for the current switches for the switched current power converter (SCPC). The logic and controls of the SCPC are amazingly simple and easily integrated. More important to its commercial success is the cost effective manufacture of the power IC, as it competes with discrete MOSFETs. (See "Switched Current Power Converters" , Edward Herbert, January 20, 2005.)

There are many other applications for simple power ICs, which are discussed below.

Power integration: The pros and cons:

There are many advantages to integrating logic circuits and gate drivers with MOSFETs as power ICs, but the cost penalty is high because it requires the MOSFET to go through many more manufacturing steps. In some applications, the additional processing steps can be too expensive for economic viability. While a MOSFET has 4 or 5 mask levels, a fully integrated BCDMOS IC has 15 to 20 or more.

The solution: Partial integration;

If all of the MOSFETs of a power IC are the same type (except for active area), they can all be made using the same processing steps as a discrete MOSFET. An insulating barrier is needed to isolate the logic MOSFETs, and they must be interconnected, but this approach avoids the large number of masks and processing steps needed for a fully integrated BCDMOS power IC.

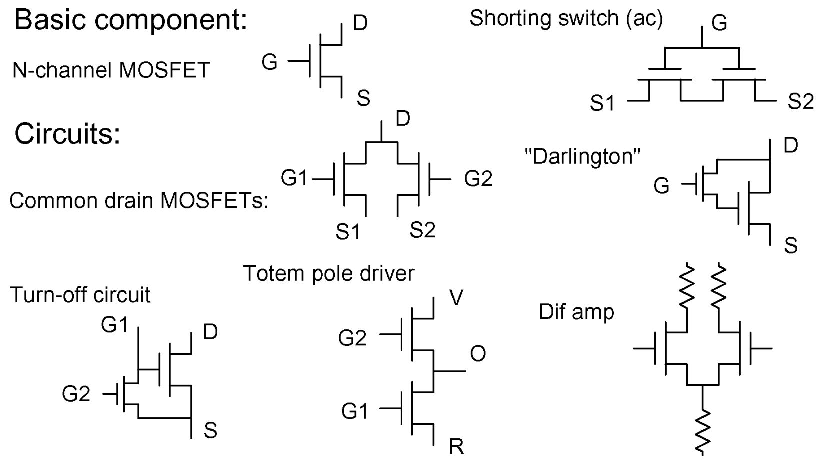
The power IC for the SCPC uses the fabrication steps of a vertical n-channel DMOS MOSFETs in which the substrate is the drain.

The SCPC logic and power ICs.

The master control, logic and high side drivers are in a conventional IC, while the power MOSFETs and the low side drivers are in a simple power IC. This division of function optimizes both ICs, keeping the power IC very simple and inexpensive, and providing the advantages of integration without the cost penalties.

The component "inventory":

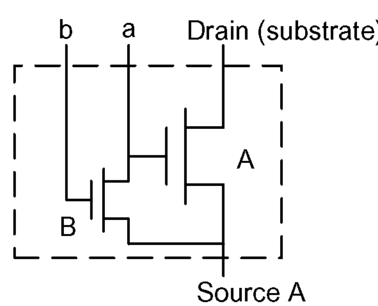
While using only one type of MOSFET (except for active area) limits design options, it keeps the number of manufacturing steps to a minimum and controls cost. Using only n-channel MOSFETs, the following circuits can be assembled.



With resistors, many more circuits based upon the old RTL integrated circuit logic family (from the 1960's) can be made, by substituting n-channel MOSFETs for the NPN bipolar transistors.

The logic divide:

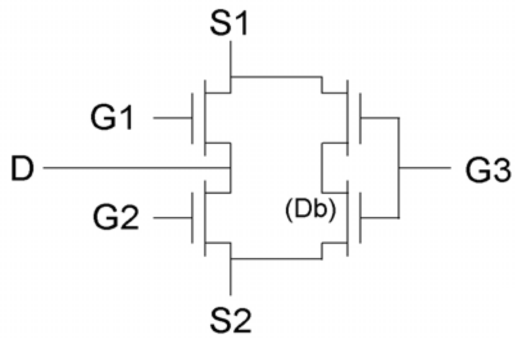
In the SCPC, all of the switched current outputs have a common output terminal, Vo, and all are the drains of power MOSFETs. Therefore, all of the power MOSFETs of the SCPC can be on one substrate, and the substrate is the common drain and Vo output for all of channels. Two channels per power IC may be optimum for a higher current SCPC (> 100 A), as that optimizes the transformer interconnections. All of the power components of a lower current SCPC can be entirely on one power IC.



As an introduction, in the partial schematic shown, MOSFET A is the power MOSFET. Its drain is the common drain (the substrate), and it has a source terminal A and a gate terminal a. A low side driver MOSFET B is connected from the gate of the MOSFET A to its source, to turn off MOSFET A very rapidly when gate b is turned on. The drain of the MOSFET B must be isolated, but its source is common to the source of the MOSFET A. Turning on the MOSFET A is much less critical, so it is turned on conventionally with a signal applied to its gate a by the high side driver located in the logic IC.

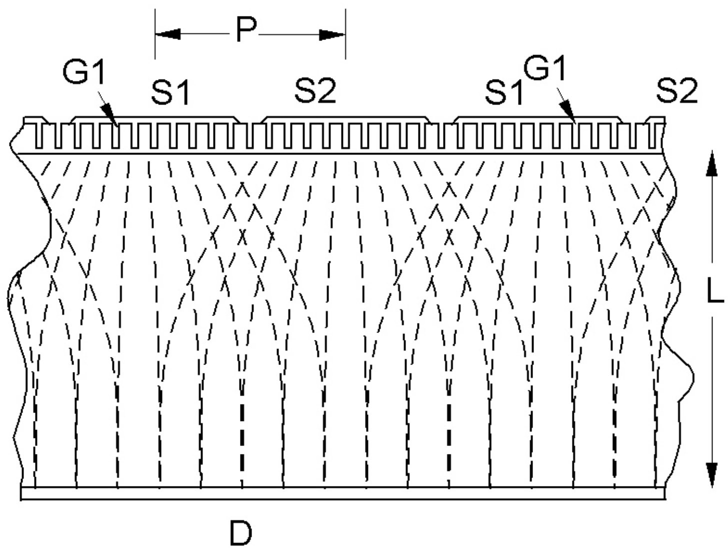
The MOSFETs "A" and "B" are the same except for their active area, and are made at the same time using the same manufacturing processing steps.

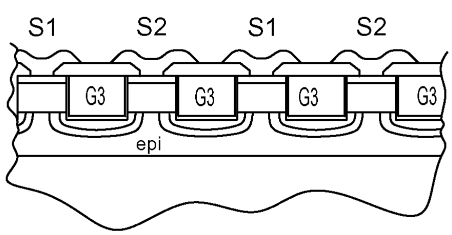
The SCPC power IC:



The transformer version of the SCPC uses two MOSFETs for each channel as synchronous rectifiers. During the "on" time, the synchronous rectifiers are turned on alternately, timed by a master clock for all channels. During the "off" time, both synchronous rectifiers are turned off, and a shorting switch is turned on.

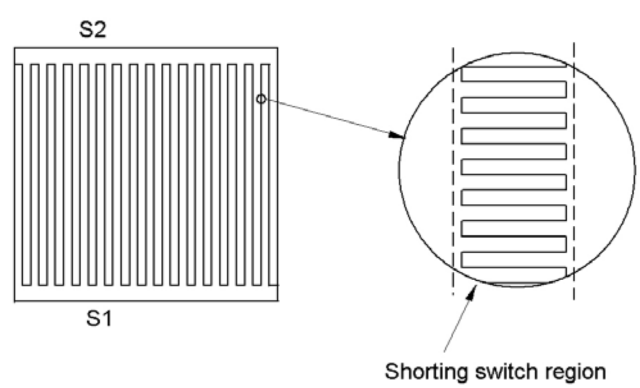
Both of the synchronous rectifier MOSFETs share the common drain connection D, but their sources S1 and S2 and gates G1 and G2 are separate. If the sources are interdigitated, with a pitch P that is small compared to the die thickness L, the area of the drain D is shared and the current density at the drain is halved. High frequency effects are minimized.





In the schematic, the shorting switch looks like two devices, two MOSFETs back to back, functionally, and it must block current in either direction when off. In the power IC, the shorting switch is implemented using single trenches with a common gate G3. The sources S1 and S2 are interdigitated alternately on opposite sides of adjacent trenches. No separate terminations are needed, as they are common to the source terminations of the synchronous rectifiers, and all of the process steps are the same as used to make the MOSFETs on the power IC.

The conduction paths for the shorting switch are the small loops shown under the trenches. This path is very short and they can be massively paralleled, for very low on resistance. The terminations are solder bumps.



The shorting switch can occupy the margins between the sources of the synchronous rectifiers. The drains of the shorting switch are buried and require no connection. However, they must be isolated from the other circuits, so there is an isolation barrier under the area occupied by the shorting switch.

Additional logic may be incorporated into the simple power IC, and if only the same type of MOSFET is used, differing from the power MOSFETs only in active area, no additional manufacturing steps are required to make them, only the underlying isolation layer barrier and interconnections.

The SCPC simple power IC die may contain two channels: four synchronous rectifiers, two shorting switches, and their low side drivers. The low side drivers are identical n-channel MOSFETS as the synchronous rectifiers and are made at the same time with the same processing steps, except that they have much smaller active areas and also have an underlying insulating barrier, as do the shorting switches. The substrate is the common drain connection for all four of the synchronous rectifiers, and it is the output voltage Vo connection of the SCPC.

A SCPC for lower current applications can have all of its channels on one simple power IC. The circuit partitioning among the power ICs for a SCPCis determined partly by the total current that a die can handle, and partly to optimize the transformer secondary connections for minimal stray inductance.

Power IC manufacture:

The power IC is made exactly as a discrete n-channel MOSFET would be made, with a few extra steps:

After die preparation, and before the epitaxial layer is deposited, an insulating oxide layer is added to the die, then it is etched away except where the isolated MOSFETs and shorting switches are to be located.

All of the usual manufacturing steps for making a n-channel vertical DMOS MOSFET follow: diffusing layers in the epitaxial layer, etching the trenches, and so forth. When the trenches are etched, trenches defining the boundaries of the isolated MOSFETs are etched as well, but more deeply, down to the insulating oxide layer.

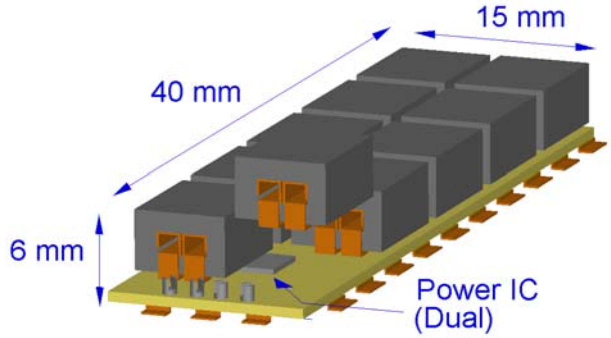
The gate oxide layer is formed, the gate polysilicon is formed, and so forth, using exactly the same steps as in making a discrete DMOS MOSFET.

An extra metallization layer interconnects the logic. Then the source and gate metalizations are deposited, just as in a discrete MOSFET except that there will be more source and gate pads and connection pads for the logic.

A connection to the substrate is needed for the SCPC common output, but all other connections are solder bumps on the surface of the die.

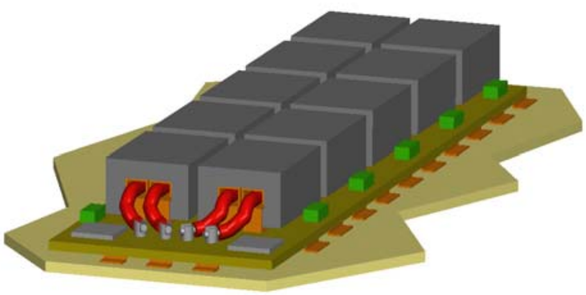
The SCPC module:

The transformers and the power ICs are placed on a flat daughterboard, and the primary windings (a pair of "U" shaped wires) are installed and terminated. The flat placement of the transformer cores is not optimum, but may be preferred for its lower profile.



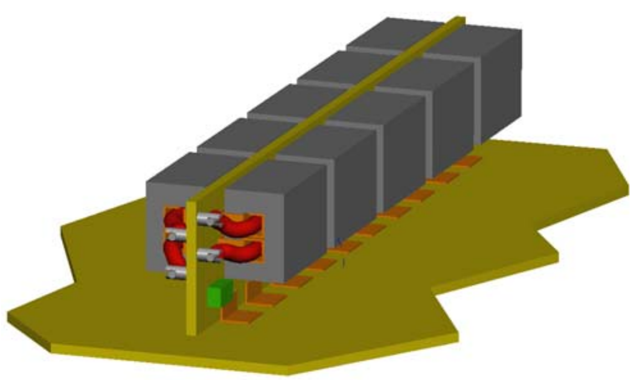
In the module shown, one of the transformer cores is lifted, to show the power IC under the transformers on the daughter board. Components can also be placed on the under side of the daughterboard.

If the size of the daughterboard is increased slightly, the entire SCPC circuit can be included. A master IC and a primary driver IC are added, as well as small decoupling capacitors. Additional MLCC capacitors are on the motherboard, close to the processor. No bulk capacitors are used with the SCPC.



The components of the SCPC could be directly installed on the motherboard, but there are advantages to using a separate daughterboard. All of the fine pitch connections for the solder bumps are confined to the small daughter board, and the entire circuit can be tested before assembly.

There is flexibility in the layout and arrangement of the components of the SCPC. For example, where motherboard space is at a premium but there is adequate headroom, the circuit can be used on edge.



Other applications for simple power ICs:

The simple power ICs developed for the SCPC can be used in many other applications. Because the simple power IC design is based upon n-channel DMOS MOSFET design, it is modified for other voltages and currents just as a corresponding discrete MOSFET is.

The shorting switch is a new circuit component, without a MOSFET equivalent, but it uses the same fabrication steps and can be modified for different voltage and current ratings the same way that a discrete MOSFET is. (The closest similar circuit is back-to-back MOSFETs with common drains, and with their gates connected together).

It is always an option to include drivers and other logic. If they are restricted to the same process steps as the power MOSFETs, the benefit is significant, with very little cost.

Synchronous rectifiers

There are many applications for synchronous rectifiers, and the substitution of an IC with low side drivers will reduce the part counts and increase performance.

One application in particular is becoming very popular, the "dc-dc transformer". A dc-dc transformer using matrix transformers is particularly well suited for the simple power IC. For lower current applications, all of the synchronous rectifiers can be on one substrate. For higher current, the optimum partition is dual channel simple power ICs located very close to the transformer terminals.

Synchronous rectifiers with a shorting switch

A "dc-dc transformer" made with a matrix transformer can change its equivalent turns ratio if one or more section has synchronous rectifiers plus a shorting switch (exactly as in the SCPC power IC). This allows the dc-dc transformer to have an accurate output voltage even with significant line and load changes. As an example, a matrix transformer with a switchable turns ratio, say 14 to 1 to 10 to l can provide an accurate 1.00 volt output with an input voltage from 10 to 14 volts. Above and below this range, the output voltage is well behaved. For the example, a 14 section matrix transformer has shorting switches on the synchronous rectifiers of four of the transformer sections, so that the ratio can be pulse width modulated to control the output voltage to the desired precision. Filtering can be a small inductor on the input and a small capacitor on the output.

For lower current applications, all of the synchronous rectifiers and shorting switches can be on one substrate.

Shorting switch

The shorting switch described above is an ac switch, that is, it can block current in both directions when off. Because its conduction path is just the distance under the trenches, and the trenches can be very densely spaced, it is a very low impedance device with its terminations on the surface of the IC die. If the shorting switch is used alone as a discrete component, no buried oxide layer is needed, and it is equivalent to two MOSFETs connected back-to-back with a common drain and connected gates. This complex equivalent circuit belies its simplicity: it's just a trench with oxide and a gate.

One application for such a device, a very small device, is the switch used for reverse voltage protection in cell phones and similar applications.

There are commercially available MOSFETs that uses lateral MOSFETs to achieve very low on resistance, partly as a benefit of having all of its connections as solder bumps on the face of the IC. The shorting switch has the same advantage, but being a trench device, the density is much higher. (A note of caution: if making a part substitution for a MOSFET, be sure that the application does not use and rely upon the diode characteristics of a MOSFET in the reverse direction.)

There are many applications at higher voltages where an ac switch can simplify the design and improve the efficiency. As an example, consider an ac input with full wave rectifiers and a n-channel MOSFET. Ac shorting switches can be used, eliminating the rectifiers (and their inefficiency).

Totem-pole driver (buck converter)

Totem-pole drivers are used in many places. The MOSFET drivers for a buck converter is a very common example. The input of an inductor is switched either to a positive input voltage or to ground. When switched to ground, a low resistance is very important.

A simple power IC totem pole driver can be integrated into a DMOS MOSFET die with the substrate as the connection to the positive input voltage. The top surface of the die has two power terminations: one is the source of a vertical MOSFET, and the other is a second source, connected to the first through a shorting switch. When the MOSFET is on, the IC acts as a discrete MOSFET, but the drain has lower current density. When the shorting switch is on, there is a very low impedance switch with its terminations entirely on the top surface of the die, for very low resistance using solder bumps.

The low side drivers can be integrated into the die as well, with significant performance benefit and little cost.

Synthetic rectifiers

The synthetic rectifier is a MOSFET device that has associated controls to simulate an ideal rectifier. The high current section of the synthetic rectifier is a MOSFET that is divided into a large number of cells. As the current decreases, the cells turn off in groups as the current decreases so that as zero crossing is approached, only a few cells remain on and they can be turned off very rapidly, to prevent significant reverse recovery current. See: U. S. Patent No. 6,992,906, "Synthetic Rectifiers".

The cells contain low side drivers for very fast response for turn off. For a precision synthetic rectifier, a separate control IC contains the logic and the high side drivers. A simpler synthetic rectifier uses only n-channel MOSFETs that are made with the same process, differing from the higher current MOSFETs only in their active area. Dif amps sense the current and shut down cells in groups as the current goes to zero.

An alternative bilateral rectifier device uses the shorting switch described above, and has two control leads. If both leads are low, the device is off. If both are high, the device conducts current in both directions. If only one of the input controls is high, the device is a near ideal rectifier with reversible polarity depending upon which control input is high.

MOSFETs with integrated low side driver

Any power MOSFET has improved performance, particularly during turn off, if its low side gate drive is incorporated into the device. By using logic and gate driver MOSFETs which differ only in their active area for the low side drive, this can be done with very little cost difference.

Very fast turn-off eliminates the Miller effect:

If the gate current exceeds the drain current at turn-off, the consequences of the Miller effect are greatly reduced and the losses due to crossover power are much less. While this results in a high current spike from the gate, it is entirely within the power IC through the low side gate driver MOSFET. As there is no parasitic inductance in this circuit, there is no voltage spike or emi attributable to the gate current discharge. See: U. S. Patent No. 6,992,520 "Gate Drive Method and Apparatus for Reducing Losses in the Switching of MOSFETs "

This drive is particularly useful for switching clamped inductive loads, such as a transformer primary. The transformer preferably has very low leakage inductance, and the coaxial push-pull transformer is suggested. See: Coaxial Push Pull Transformers (pdf) .

More complex power ICs using simple power IC processing:

One of the earliest integrated circuit technologies, introduced in the '60s, used only NPN transistors and resistors. It was called RTL logic, for Resistor-Transistor Logic and operated on 3 volts. See http://www.semiconfareast.com/rtl.htm. A variant was DCTL, for Direct Coupled Transistor Logic. Although quite limited, a number of useful functions were commercially available, NAND gates, NOR gates, R-S flip-flops, and eventually many more.

Although designed as digital logic, RTL logic was sometimes used as analog circuits by resourceful engineers of that era. This was an uncertain process, often requiring a lot of improvisation and tweaking, but it did work and was an opportunity to miniaturize circuits for the first time.

The significance for the simple power IC is that many of the RTL circuits can be adapted to MOSFETs and simple digital logic and analog circuits can be made using one type of MOSFET, varying only in their active areas, as long as isolation and interconnection can be provided. While they cannot equal the functionality of a full integrated circuit, they can be made using the process used for DMOS MOSFETs, with just a few extra processing steps.

Patents:

Patents are pending.