SOLID STATE RF POWER: THE ROUTE TO 1W PER EURO CENT

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Abstract

In most particle accelerators RF power is a decisive design constraint due to high costs and relative inflexibility of current electron beam based RF sources, i.e. Klystrons, Magnetrons, Tetrodes etc. At VHF/UHF frequencies the transition to solid state devices promises to fundamentally change the situation. Recent progress brings 1 Watt per Euro cent installed cost within reach. We present a Silicon Carbide semiconductor solution utilising the Solid State Direct Drive™ [1-3] technology at unprecedented efficiency, power levels and power densities. The proposed solution allows retrofitting of existing RF accelerators and opens the route to novel particle accelerator concepts.

INTRODUCTION

Traditionally high power RF sources have been the preserve of electron tube technology, with Klystrons being used above 300MHz and Tetrodes etc below 300MHz. Whilst solid state RF solutions have been used extensively in the RF arena these are typically based on silicon technology at relatively low power optimised for the communications industry. Within the particle accelerator community there are relatively few solid state solutions. To date the highest power installed system is the 352 MHz, 190 kW, CW amplifier for the SOLEIL synchrotron (France) commissioned in 2005 [4]. Initial results from the Cryoelectra concept have also achieved 150kW at 170MHz [5]. However utilisation of silicon as a base technology has experienced fundamental limits on the scalability to higher RF power levels. Replacing silicon by wide bandgap semiconductors like silicon carbide (SiC) and gallium nitride (GaN) seems to be a more promising approach.

The traditional view is that that these materials represent no cost advantage over silicon and even electron tube technology because of their excessive device and circuit cost implications. We herewith present a silicon carbide based approach which overcomes these shortcoming, and results in a very competitive cost position compared to established RF power technologies.

SIC TRANSISTOR PROGRAM

SiC is intrinsically a much superior RF electronics material than Si in terms of speed, breakdown voltage, heat conduction, achievable power density, ruggedness and radiation hardness. For our program we use vertical JFETs. A stylised depiction of the basic cell geometry is displayed in Fig. 1. A single transistor consists of several thousand cells with a combined active area of ~4 mm^2. Such devices have been extensively developed for kHz class switch mode PSU applications. For higher frequency applications some optimisation of the cell geometry is required. In particular the gate resistance and capacitance assume a critical importance as this determine the time constant for charging and discharging the gate and consequently determines the frequency response and maximum gain [6]. Figure 1b shows the physical definition of these capacitances.

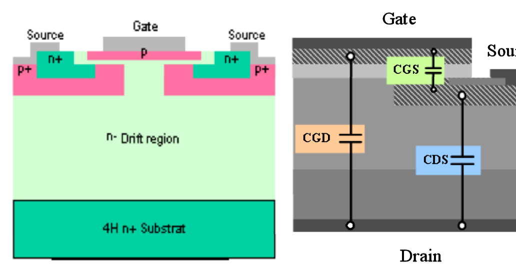

Figure 1: Simplified diagram of a v-JFET cell.

Pulsed DC measurements of the output characteristics are shown in Figure 2. The peak drain current is clearly dependent upon the FET channel temperature. Our device achieves 50A with a cold channel, which reduces to 30A after some 100 microseconds of intense heating due to short circuited operation.

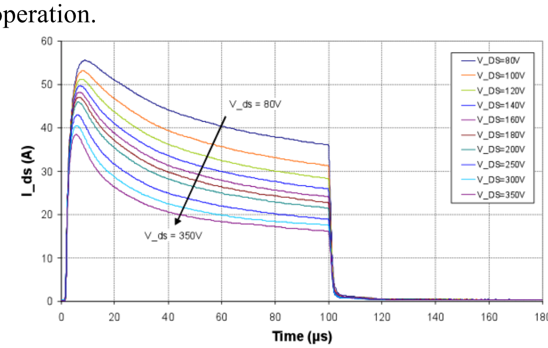

Figure 2: Drain current as a function of pulse duration for several different drain voltages.

The measured device transfer characteristics of the device are shown in Fig. 3. The channel pinch-off voltage is about -16V. The gate voltage – drain current characteristics is a bit more linear than the ideal quadratic dependence, which benefits the linearity of amplifiers built with this device.

The frequency response of the transistor was obtained by making small signal measurements of the maximum gain (G_{max}) over a range of drain-source voltages (V_{DS}) and frequencies. These results are shown in Fig. 4. Generally G_{max} grows with the supply voltage V_{DS} but decreases with increasing frequency.

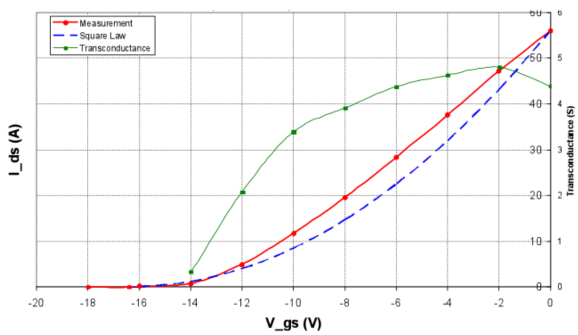

Figure 3: The measured U_{GS} – I_D transfer function and transconductance for our current SiC vJFET.

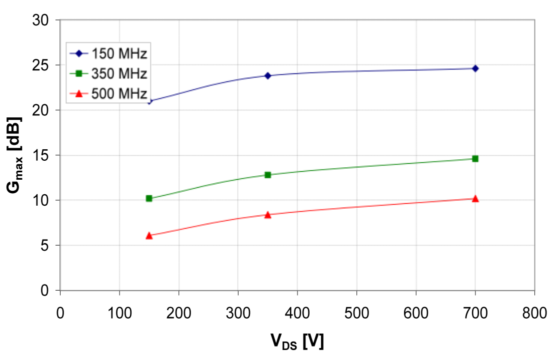

Figure 4: Gmax measurements as a function of drain – source voltage for several frequencies are plotted.

Although small signal measurements can give a general indication of frequency scaling they, are not too useful for precise large signal performance prediction. Full RF power tests were undertaken at 150MHz (see Fig. 5).

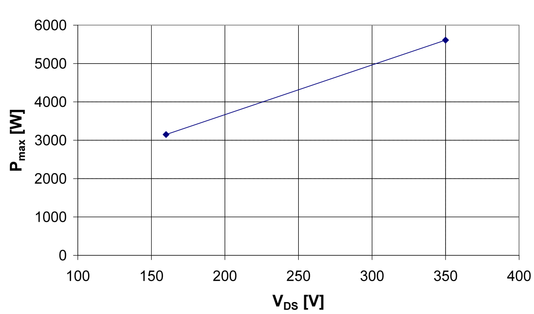

Figure 5: Output power of a single transistor in class AB at 150MHz over DC supply voltage.

In single ended class AB operation we reached power levels in excess of 5kW per transistor at 350V, which was less than 25% of the maximum V_{ds} capability, so 10kW RF power per transistor should easily be reachable for short bursts. The average power level is solely determined by the power stage efficiency and the device cooling ability. Class F operation promises >85% efficiency, which would allow >1kW average RF power on our 4mm^2 device. The power measurements also show that the actual gain at high power levels is approximately 1.5dB lower than derived from small signal measurements.

POWER COMBINER

Particle accelerators typically require RF pulse power levels in the MW range or CW power levels of 10's of kW. Such power levels still necessitate combining the output of several transistors. In the Solid State Direct Drive™ system [1-3] power combining is done in two stages. In the first stage 8 transistors form a single class F parallel push-pull stage with an output power of about 50kW at 325MHz (see Fig. 6). MW power levels can be reached by combining the output of a sufficient number of modules into a single load. A more in-depth description of our RF power combiner technology can be found in [1-3,6].

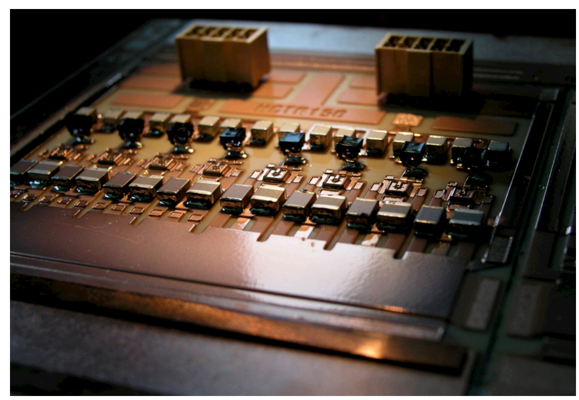

Figure 6: 8 transistor 325MHz RF power module. 50kW pulsed RF power, 80x60mm^2 board size.

COST POSITION

The SiC device cost are seemingly driven by development costs in the face of a small market. The economics of scale promise to reduce the cost to levels known from Si devices with similar power rating. The unique properties of wide bandgap semiconductors like SiC and GaN have far reaching secondary effects on the costs of the surrounding circuitry and board:

- Reflected RF power does not destroy the devices due to superfast body diodes. This obviates the need for RF circulators or other protection strategies.
- Our devices can be parallelized without any protection measures.
- The robustness of SiC allows extreme power densities. This is especially valid for pulsed operation in RF accelerator applications.
- Wide bandgap semiconductors tend to be radiation hard, which allows a closer integration of RF generator and particle accelerator cavities.

- The voltage levels are in the range of standard consumer electronic devices, which allows massive economics of scale.
- The power stage can be gated, i.e. no pulse power supply is necessary.
- The modular architecture allows graceful degradation under point failures, and thus preventive maintenance schemes.
- The modular architecture also allows covering various RF power requirements with a single underlying RF module design. The power combiner is then the only variable.

A cost of 1 Euro cent per Watt RF power seems easily reachable.

DISCUSSION

High band gap semiconductors like SiC and GaN and a modular architecture promise to change the law of economics in solid state RF power sources. It seems that for VHF and UHF frequencies electron tubes finally become superseded by solid state solutions even at highest RF power levels.

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