Setup of Cryogenic Front-End Electronic Systems for Germanium Detectors Read-Out

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Front-end electronic devices for the read-out of ionizing radiation sensors must operate in many cases at cryogenic temperatures. Sometimes the front-end circuit is divided into a cold part operated at cryogenic temperature and a warm part operated at room temperature outside the cryostat. In other cases this is not possible owing to the physical constraints coming from the experimental setup, the detector system requirements or the apparatus geometry. In this latter cases the front-end circuitry has to operate in its entirety at cryogenic temperature. In this work, carried on in the framework of the GERDA experiment (GERmanium Detector Array), we focus in particular on front-end read-out systems for High-Purity Germanium (HPGe) detectors, which are usually operated at liquid nitrogen (LN) temperature. We study the strong effects that the changed characteristics of the electronic active and passive devices have on the charge preamplifier design when operated in LN, while taking into account the particularly challenging requirements that the circuit has to meet: radio-purity, physical reliability under thermal cycling, good noise performance (0.1-0.2% resolutions) and fast rise time (20 ns) needed for pulse shape analysis applications. We discuss in particular the effects that changes of JFET and MOSFET transconductance have on noise and bandwidth performance of the front-end circuit. We also discuss the effects that a changed performance of passive devices, such as high-value filtering capacitances, may have on the preamplifier response when operated in LN.

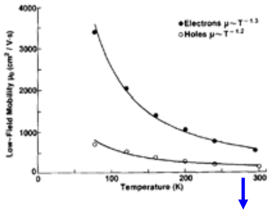
Requirements for cryogenic charge sensitive preamplifiers for High-Purity Germanium detectors

- Full functionality at cryogenic temperature (77K in liquid nitrogen, 86K in liquid argon)
- Physical reliability under thermal cycling
- High degree of radio-purity (when inserted in ultra-low background radiation detection systems)
- Low noise (gamma spectroscopy grade: 0.1-0.2 % - the intrinsic resolution of large-volume HPGe detectors is ~1.6 keV @ 1.3 MeV)
- Excellent stability of the gain (loop gain of the order of 10^3)
- Wide bandwidth: rise time of ~ 20 ns (in order to apply the pulse shape analysis algorithms)
- Large dynamic range: at least ~10^3 (10 keV -10 MeV)
- Low power consumption (~20-40mW per read-out channel)
- Output stage able to drive long 50Ω–terminated coaxial cables

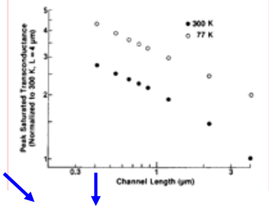
Room temperature (300K) vs. cryogenic temperature (77K) behavior of active and passive devices

Silicon <u>Bipolar Junction Transistors (BJTs)</u> cannot operate at 77K, because their performances are completely spoiled by freeze-out phenomena.

For a <u>MOSFET</u> of a given geometry, transconductance is proportional to the drift velocity in the channel. At low channel fields (long channel, small drain voltage) transconductance is proportional to the low-field carrier mobility. Mobility increases while decreasing the temperature from 300K to 77K by a factor of 4-6, because of the reduced carrier scattering due to lattice vibration. This increase in mobility is also observed on long channels in the saturation mode, where it can be assumed that the drift velocity in the channel is proportional to the longitudinal field.

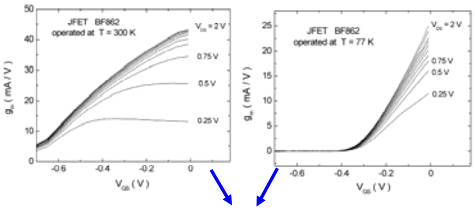


Temperature dependence of channel mobility for both electrons (NMOS) and holes (PMOS), as measured in the linear mode on a 0.5 μm CMOS technology.

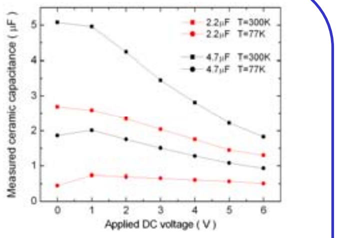


W.F.Clark, B.El-Kareh, R.G.Pires, S.L.Titcomb and R.L.Anderson, "Low temperature CMOS-A brief review", IEEE Trans. Comp. Hybrids, Manuf. Technol., vol. 15, pp. 397-404, 1992

The <u>Silicon JFET</u> transconductance increases while temperature decreases down to 120K. Then the transconductance decreases again, owing to the increased scattering due to impurities in the lattice. At about 40K the JFET stops working because of carrier freeze-out. As the transconductance is inversely proportional to the thermal noise, the operating point at 120K is the optimal one. The choice of using a JFET as input transistor at 77K, even though thermal noise is not optimized, can be dictated by the extremely low level of 1/f-like noise that JFETs exhibit, which can be particularly important for spectroscopic applications

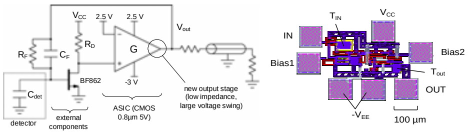


Measured transconductance of the BF862 JFET manufactured by Philips: a drop of a factor 5 is measured at 77K



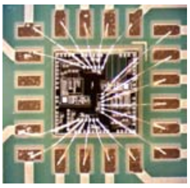
<u>Resistances</u> and <u>low-value ceramic capacitances</u> maintain their properties and values when cooled down to 77K. But this is no more true for <u>high-value ceramic capacitances</u>. We tested the behavior of high-value (some μF) and small size (0603) ceramic capacitances made of dielectrics of high dielectric constant (X5R, Y5R). When the applied DC voltage is increased, the measured capacitance value decreases, in particular when the applied voltage is close to the maximum rating, even at room temperature. As shown in the figure, when the tested capacitances are cooled to 77K, their value decreases really dramatically. In liquid nitrogen, with an applied 3V-DC voltage, the loss in the capacitance value is of 70 %.

3-channels cryogenic preamplifier for the HPGe detectors of GERDA



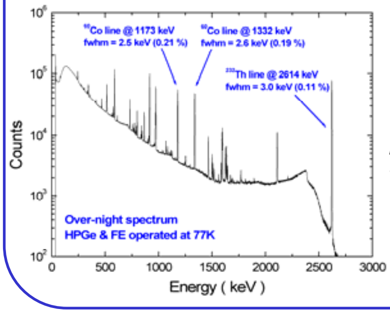
Single-channel preamplifier scheme and ASIC layout. The ASIC has been realized in a mature CMOS CXZ 0.8 μm 5V technology provided by Austria Micro Systems. The area occupancy of the ASIC is as little as 366×275 μm² excluding the bonding pads.

"Top" side of the 3-channels PCB



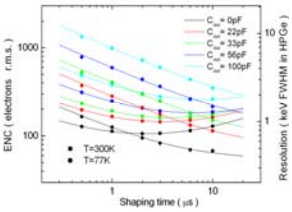
"Bottom" side of the 3-channels PCB

3-channels ASIC as mounted and bonded directly on the bottom side of the PCB, because a standard ceramic carrier would not meet the radio-purity requirements.



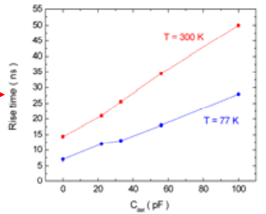
Spectrum acquired over-night with the 3-channels PCB operated inside a liquid nitrogen dewar and connected to the outside through 12-m long RG168 cables

Noise and bandwidth performance of the realized preamplifier at 300K and 77K



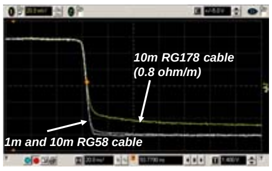
Parallel white noise contribution substantially decreases at 77K as expected. The decreased temperature only partially compensates the effect of a decreased transconductance, so that the overall series white noise is higher at 77 K than at room temperature.

The drop in the JFET transconductance at 77 K may be expected to determine a drop in the preamplifier bandwidth too. The opposite result is instead found: the preamplifier bandwidth increases when the circuit is operated at cryogenic temperature, owing to the much higher increase of MOSFET transconductance.

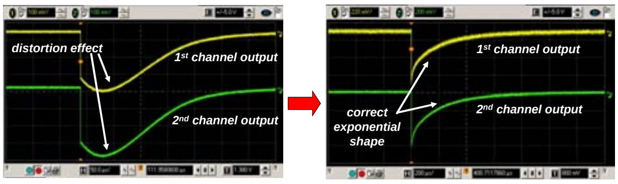


Disturbing effects of the cryogenic setup on the preamplifier performances

- ✓ **The <u>spoiled performance of the high-value ceramic capacitances</u> yields disturbing effects on the shape of the preamplifier response: when large and fast signals have to be provided on a low output load (like a terminated coaxial cable), the circuit has to deliver a considerable power in the fastest possible time and this is achieved by means of the charge stored on the high-value capacitances used for power supplies filtering ➔ tantalum capacitors, maintaining their constant value at 77K, can be used at the expenses of a high dissipation factor.**
- ✓ **Use of thin cables is mandatory to achieve a high level of flexibility and maintain a maximum level of radio-purity, at the expenses of a <u>high cable resistance</u> up to 0.8-0.9 ohm/m. Since long cables (10-12m) may be needed in a large-dimensions cryogenic setup (like that of GERDA) to connect the circuit with the outside, a series resistance of 10-12 ohm may be present along power supplies cables.**
- ✓ **<u>Power-supply bounce</u> is encountered due to the high resistance cables and its effect gets enhanced by the lack of a needed filtering capacitance. This can also yield <u>cross-talk effects in multi-channel configurations</u> ➔ a particular care must be used in separating power supplies of the input and output stages, so as to separate the main gain stages from the stages where power has to be delivered.**



Effect of the <u>cable resistance</u> on the shape and amplitude of a pulser test signal. Use of long and thin cable is often mandatory in cryogenic setup.



Output signal of two different preamplifier channels operated at 77K and connected to the outside through 12-m RG168 cables: when one common power supply is used, and a considerable power has to be delivered, the output exponential signal shape is distorted by the <u>bounce effect on the common power supply</u>. An appropriate separation of the input/output stages power supplies is mandatory to eliminate the distortion.