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 dependence 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 that a changed performance of passive devices, such as high-value filtering capacitances, may have on the preamplifier response when operated in LN.

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

The Silicon JET 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 JET 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.

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 at 1.3 MeV)
- Excellent stability of the gain (loop gain of the order of 10)
- Wide bandwidth: rise time of ~ 20 ns (in order to apply the pulse shape analysis algorithms)
- Large dynamic range: at least ~10 (10 keV -10 MeV)
- Low power consumption (~20-40mW per read-out channel)
- Output stage able to drive long 50±-terminated coaxial cables

Disturbing effects of the cryogenic setup on the preamplifier performances

- The applied performance of the high-value ceramic capacitances 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 high cable resistance, up to 0.3-0.5 Ohm. 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.
- Power-supply bounce is encountered due to the high resistance cables and its effect gets enhanced by the lack of a needed filtering capacitor. This can also yield cross-talk effects in multi-channel configurations.
- 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.

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

For a MOSFET 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.

Silicon JFETs for the HPGe detectors of GERDA...