The Majorana low-noise low-background front-end electronics

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Abstract

The MAJORANA DEMONSTRATOR will search for the neutrinoless double beta decay ($\beta\beta(0\nu)$) of the isotope ^{76}Ge with a mixed array of enriched and natural germanium detectors. In view of the next generation of tonne-scale germanium-based $\beta\beta(0\nu)$-decay searches, a major goal of the MAJORANA DEMONSTRATOR is to demonstrate a path forward to achieving a background rate at or below 1 cnt/(ROI-t-y) in the 4 keV region of interest (ROI) around the 2039-keV Q-value of the ^{76}Ge $\beta\beta(0\nu)$-decay. Such a requirement on the background level significantly constrains the design of the readout electronics, which is further driven by noise and energy resolution performances. We present here the low-noise low-background front-end electronics developed for the low-capacitance p-type point contact (P-PC) germanium detectors of the MAJORANA DEMONSTRATOR. This resistive-feedback front-end, specifically designed to have low mass, is fabricated on a radioassayed fused-silica substrate where the feedback resistor consists of a sputtered thin film of high purity amorphous germanium and the feedback capacitor is based on the capacitance between gold conductive traces.

1. Introduction

The next generation of tonne-scale germanium-based $\beta\beta(0\nu)$-decay searches will probe the neutrino mass scale in the inverted-hierarchy region. Several smaller detectors are being either constructed or operated in order to demonstrate their scalability to a larger experiment at an ultralow radioactive background level. The modular and readily scalable design of arrays of germanium detectors of the MAJORANA DEMONSTRATOR [1] provides a fast deployment with minimum interference on already-operational detectors. The use of intrinsically low-background source material at each step of construction aims at the reduction of environmental ionizing radiation backgrounds by about a factor 100 below what has been achieved in previous experiments. In particular, the resistive-feedback front-end readout electronics of the MAJORANA DEMONSTRATOR is specifically designed to have low mass and have minimal impact on the overall background budget.

In what follows, Section 2 presents the low-noise design of the MAJORANA front-end electronics while Section 3 describes the low mass fabrication and reviews the front-end functionality at cryogenic temperatures.

2. Low-noise design

An overview of the MAJORANA resistive-feedback charge-sensitive preamplifier is given in Fig. 1 (top left). The front-end, consisting of an n-channel JFET, feedback and charge injection components, is part of a first amplification stage followed by an AC-coupled second stage that provides a differential dual-gain output for digitization. As low readout electronics noise is a key component for background rejection in the MAJORANA DEMONSTRATOR, this readout electronics design optimizes noise performance based on 1) low input capacitive load, 2) minimal stray input capacitance, 3) intrinsically low-noise front-end components.

Aside of their pulse shape discrimination capabilities, the P-PC detectors of the MAJORANA DEMONSTRATOR provide a low input capacitive load with a capacitance of about 1-2 pF at full depletion voltage, an order of magnitude lower than conventional germanium detectors with a coaxial geometry. The stray input capacitance is minimized having the LMFE mounted as close as possible to the detector's p+ charge-collection contact in a DC-coupled configuration. As illustrated in Fig. 1 (bottom left), this is achieved by separating the front-end from the first amplification stage and operating it at cryogenic temperatures close to the detectors. The front-end is connected to the rest of the preamplifier, operated ouside the cryostat at room
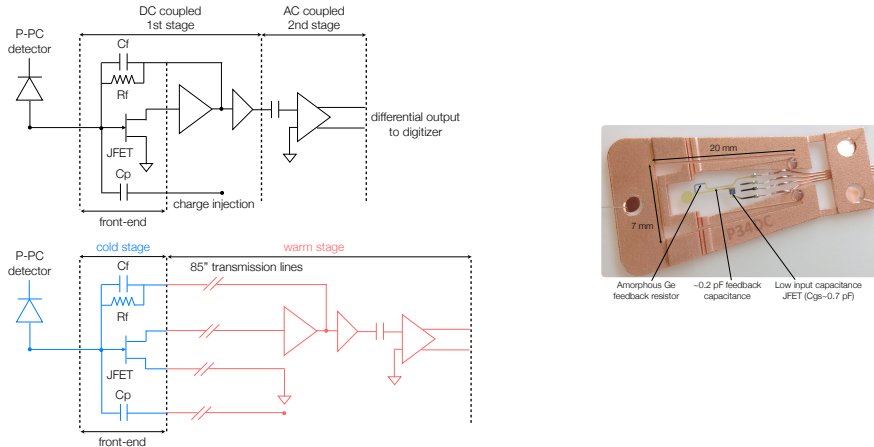
Fig. 1. Top left: simplified diagram of the MAJORANA resistive-feedback charge-sensitive preamplifier. Bottom left: actual setup with front-end operated at cryogenic temperatures inside the cryostat. Right: the MAJORANA front-end mounted on its supporting copper clip.

temperature, with long (2.15 m) coaxial transmission lines. Fig. 1 (right) shows the front-end mounted on its supporting copper clip. The three-terminal n-channel JFET from MOXTEK [3] has a very low built-in input capacitance (Cgs~ 0.7 pF) and both the high resistivity (~10 GOhm at 90 K) amorphous germanium feedback resistor and amorphous silicon dioxide substrate are characterized by a low *1/f* noise.
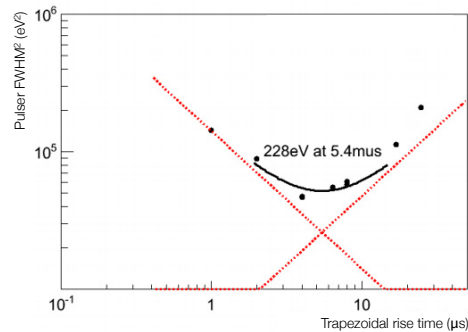

Fig. 2. Left: multi-detector system (*string*) including the copper mounts and cabling length of the MAJORANA DEMONSTRATOR. Right: noise curve of front-end operated in a *string* as a function of shaping time.

A prototype front-end tested without detector load reached a minimum noise level of 55 eV FWHM. As shown in Fig. 2, the front-end mounted in a multi-detector system (referred to as a *string* of detectors) including the overall copper mounts and cabling length of the MAJORANA DEMONSTRATOR shows excellent performance with a minimum noise level achieved at 228 eV for a 5.4 μs shaping time.

3. Low-background design

The immediate proximity of the front-end electronics to the detectors in the cryostat significantly constrains the selection of materials in terms of 1) radioactive emission, 2) vacuum compatibility, 3) functionality at or near 80 K.

The radiopurity of the board, summarized in Tab. 1, is controlled by using high purity material, minimizing the total mass of the board and following clean handling/assembly procedures. The front-end substrate

is selected from radioactivity-assayed lots of fused silica, the feedback resistor made of a high purity germanium thin film, the traces from pure Au-Ti and the bare JFET die ($0.9 \times 0.9 \times 0.51$ mm^3) from pure silicon substrate. Al-Si bonding wire and clean silver epoxy are used to connect the JFET die and coaxial cables to the traces. To avoid loading the board with extra components the feedback and charge injection capacitors are actually obtained from the capacitance between the on-board circuit traces. The assay results of Tab. 1 predict a total activity of 715 nBq/front-end from U and Th. This translates into a contribution of 0.27 cnts/(ROI-t-y) to the DEMONSTRATOR goal of 3 cnts/(ROI-t-y). The full-board assay results show a higher level of radioactivity still within the MAJORANA background constraint. A cleaner cleanroom was set up to improve on quality control and mitigate possible contamination during assembly.

Component	Material	Purity (g/g)	
		^{232}Th	^{238}U
Substrate	fused silica	101×10^{-12}	284×10^{-12}
Resistor	a-Ge	5×10^{-9}	5×10^{-9}
Traces	Au	$47(1) \times 10^{-9}$	$2.0(0.3) \times 10^{-9}$
Traces	Ti	$<400 \times 10^{-12}$	$<100 \times 10^{-12}$
JFET	JFET die	$<2 \times 10^{-9}$	$<141 \times 10^{-12}$
Bonding wire	Al	$91(2) \times 10^{-9}$	$9.0(0.4) \times 10^{-12}$
Epoxy	silver epoxy	$<70 \times 10^{-9}$	$<10 \times 10^{-9}$

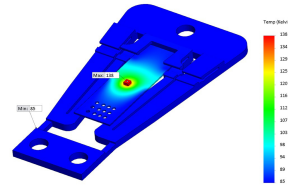Table 1. Radiopurity of the front-end components. Assay results from ICP-MS and gamma counting.

Fig. 3. Thermal gradient over the front-end thermally clamped at 85 K on its supporting copper clip for a JFET power dissipation of 40 mW and a 1000 W/m^2/K board-to-clip conductance.

The materials selected to fulfill the low background requirements must also be functional at cryogenic temperatures. The selected fused silica substrate has very low (0.5 ppm/K) thermal expansion and conductivity that assure both an optimal operating point for the JFET and thermal stability for the feedback resistor. As shown in Fig. 3, the Joule heating from the current flow in the n-channel (~30-40 mW dissipation) raises the local temperature of the JFET to about 130 K where best noise performances can be achieved. At the same time a sufficiently small and uniform temperature gradient can be kept over the thin film of amorphous germanium whose placement is critical for stability as the Ge resistance varies as $\exp(T^{-1/4})$.

4. Conclusions

As low electronics noise levels become critical for low-energy/threshold experiments, a low-mass low-noise front-end was successfully developed for the MAJORANA DEMONSTRATOR by significantly reducing the input capacitance and components intrinsic noise while keeping the background contribution within requirements by selecting radiopure materials.

The fabrication and assembly methods have been developed and the quality is consistent for large scale production. Further optimization of the low-mass front-end (LMFE) concept will make it an enabling technology for future germanium-based ton-scale experiments.

5. Acknowledgments

References

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