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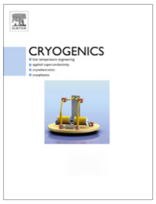

Batch screening of commercial serial flash-memory integrated circuits for low-temperature applications

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ABSTRACT

We present comprehensive results on the experimentally measured performance of commercial serial flash-memory integrated circuits (ICs) over a wide temperature range (−196 °C to 25 °C). We also address endurance issues because our intended low-temperature application is electronics related to long-term storage of biological material. We compared six batches of flash-memory ICs, manufactured between 2007 and 2012. Test results reveal a batch-to-batch variation of the pass rate. Typically, programming times increase by a factor of 4–6 at −196 °C. The practical relevance of our results is discussed.

1. Introduction

Operation of electronic components, circuits, and systems at low temperatures, called “cold electronics, low-temperature electronics, or cryoelectronics” [1,2], has an extensive history of development and use in a variety of fields, including space exploration, radio astronomy, super computers, and telecommunications. However, our focus is life-science applications such as cryogenic biobanking, which is a new, interdisciplinary field of application for cryoelectronics. In the life sciences, liquid nitrogen is used as a convenient and inexpensive coolant, and temperatures near that of liquid nitrogen (LNT = 77 K, −196 °C) are used for the preservation and long-term storage of biological materials. Especially for therapeutically relevant cells (e.g. human embryonic stem cells) efficient and reliable storage of large quantities of cells at cryogenic temperatures is crucial to guarantee permanent availability of high-quality biological material.

Ideally, electronic components for cryobiological applications should remain fully functional over the LNT to room-temperature (RT) range. Some deviation from the RT characteristics can be tolerated because circuit design and (sometimes) software can compensate. The temperature inside a cryostorage tank must remain below −130 °C (for biological reasons) and, although liquid nitrogen is used for cooling, the actual temperature seen by the ICs is typically in the −140 °C to −170 °C range. Thus, serious changes in their characteristics occurring below about −170 °C can be accepted (provided the changes are not irreversible and are not accompanied by damage).

We have developed an advanced cryotechnology platform for biological specimen banking at Fraunhofer IBMT over the last ten years [3–6]. It has several advantages over conventional cryostorage techniques: close coupling between specimen and data, automated inventory control, monitoring and recording of specimen temperature and movement, ice-free cold specimen handling, automated electronic shipping documentation, and guaranteed stability of the cold chain.

The cryoelectronic system hardware design is based on commercially available, low-voltage serial flash-memory ICs. A flash IC is inseparably built into each individual cryovial, and holds data about the specimen’s origin and type, processing description and record, as well as storage and shipment condition logs. Our latest prototype cryostorage system provides about 2000 cryovial positions, which can be extended to 18,500 positions.

The electronic circuitry is based on CMOS components, this being the technology that will operate under cryogenic conditions [7]. It is known from literature that many ICs employing cooled conventional MOS technologies, such as SRAM [8] and microprocessors [9–14], increase device speed by a factor of about 1.5–2 at low temperature. Reports on memory devices are rare: Link and May investigated transistor memory cells down to LNT [15] and Wyns and Anderson studied the behavior of commercial

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DRAMs down to 89 K [16]; both found orders-of-magnitude increase in memory retention time. Henkels et al. studied the behavior of self-designed high-speed DRAMs and found an improvement factor in access time of 1.75 at 83 K [17] while Chappell et al. found an improvement factor in access time of 1.77 at LNT [18].

However, no studies about flash-memory ICs at cryogenic temperatures are known to us. Our first evaluation of parallel flash memory for cryobiophysical applications [19] indicated write-speed improvement by a factor of about 1.5 at 83 K [3].

A major difficulty in developing cryoelectronics is obtaining suitable components, because we select from commercial-off-the-shelf (COTS) components. Very few commercial components are specified or qualified for use below −55 °C, and even fewer are designed for low-temperature operation.

So far our cryoelectronic storage system has been realized as a prototype. For the envisioned commercialization of the system and volume production of cryovials, we need efficient test systems and methods, since using COTS components at low temperatures presently requires significant qualification effort. A primary goal is to determine whether it is possible to define a test procedure at higher temperatures than LNT for the prediction of IC behavior, especially to achieve a distinct separation between passed and failed ICs, down to LNT. This would reduce test time and liquid nitrogen consumption. Thus, we have investigated serial flash-memory IC types from different manufacturers in preliminary test protocols. We used a self-designed autonomous board-level test system for the cold endurance screening and demonstrated the ability of a particular IC to operate down to LNT [5]. Following this, detailed characterization of the functionality and performance of different batches of this IC at cryogenic temperatures is required. Device behavior with decreasing temperature must be known to design peripheral electronic circuits and systems. Constraints for the volume production process of cryovials must be known, such as IC test complexity and number of known-good ICs at the lowest target temperature. Knowledge must be gathered about batch quality and yield.

The screening of every batch is necessary because of well-known problems with qualification of commercial electronic components for extreme environments. Since the components are operated out-of-specification there is a high probability for performance degradation and for batch-to-batch variation. Many fabrication parameters such as manufacturer, production site, process technology and material selection can influence the component characteristic. Tolerances smaller than kT which can be masked at RT are more pronounced at low temperatures [20]. Design modifications that leave characteristics unaltered over the manufacturer's specified temperature range may cause large changes at low temperature. Because of these factors we perform 100% qualification on every batch of certain components, primarily ICs.

In this paper we describe the test system, test method and test results for the batch screening of commercial serial flash-memory ICs and we discuss the relevance of the screening results for practical use. Although we present results for a particular IC, a key purpose of this paper is to illustrate the situation that a user of COTS components at low temperatures would likely encounter.

2. Test system design

2.1. Flash-Connector

Six batches of the same low-voltage serial flash-memory type, all from the same manufacturer and specified for operation between −40 °C and +85 °C (industrial temperature range), were selected for this study. We have tested a total number of 3600 ICs (600 ICs per batch). For confidentiality reasons, they are referred to as batch #1, #2, #3, #4, #5, and #6. They differ by their date code, process technology and assembly line employed (Table 1). These ICs are accessed by a high-speed SPI (serial peripheral interface) compatible bus and have a memory capacity of 2 Mb. They incorporate software and hardware write protection features and are packaged as 8-lead plastic small outline parts.

For the versatile use of the memory ICs in a test system, as well as for use in the cryovials, a pluggable form factor is preferred. The ICs are assembled on a small piece of PCB with chemical gold finish (FR4, 2 layers, 5.5 mm × 7.3 mm) together with a pin header (SMT, 4 + 4 pins, 1.27 mm pitch) shown in Fig. 1. Leaded solder ($Sn_{62}Ag_{0.4}Sb_{0.2}Pb_{37.4}$) is used for assemblies. This "Flash-Connector" assembly is designed to be injection-molded into individual cryovials.

We did not have any problems with the given solder composition used for prototyping. Although studies have shown that Sn-rich solders can have problems at low temperatures due to brittleness [21–24], there are also claims that adding a small amount of Sb to Sn-rich solders avoids this problem. "SnPbSb" solder has been used extensively for cryogenic wind tunnel instrumentation, and reports also tend to indicate that "SnPbSb" solder is usable down to cryogenic temperatures [25]. An extensive review of low-temperature solder literature has been compiled by Kirschman et al. [26].

2.2. Tray-board circuit

The test system consists of a USB to SPI interface (which operates at RT) driving a test tray (FR4, 4 layers, 370 mm × 371 mm), shown in Fig. 3, that can be placed in a controlled-temperature environment or immersed in liquid nitrogen. In this study, the SPI clock rate was set to 5 MHz (our previous experience with 300–400 mm boards and rather long connecting cables is that the maximum reliable clock rate is typically 8–10 MHz). Of course, actual data rates are lower due to program timing consideration and USB scheduling delays. One of the SPI *select* signals from the interface gates data into a shift register implemented in

Table 1
Batch description of serial flash-memory ICs.

Batch	Date Code	Process (nm)	Assembly
#1	0714	180	Malaysia
#2	0813	180	Malaysia
#3	0945	110	Malaysia
#4	1038	110	Malaysia
#5	1138	110	China
#6	1202	110	China

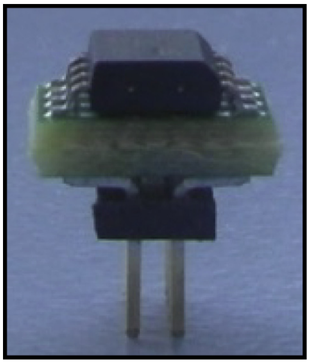

Fig. 1. Photograph of assembled Flash-Connector (5.5 mm × 7.3 mm).