Development and Implementation of a Readout Module for Radiation-Sensing Field-Effect Transistors

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Abstract—We describe a readout module for radiation-sensing field-effect transistors. Three of these modules are currently being used for measuring the total accumulated dose in the silicon vertex detector (SVD) of the Belle experiment at KEKB B-meson factory in the High energy accelerator research organization (KEK), Japan. These modules have been in operation since August 2005.

Index Terms—B Factory, MOSFET, radiation monitoring.

I. INTRODUCTION

A MOSFET that is designed specifically for radiation monitoring is called a RadFET [1]. It measures integrated radiation dose through the shift of the threshold voltage, $V_{threshold}(t)$, required to maintain a given constant drain current through a transistor. This threshold voltage shift, defined as $V_{shift}(t) = -(V_{threshold}(t) - V_{threshold}(t = 0))$ is due to the trapping of radiation-induced holes in the silicon oxide [2]. In order to operate in saturation mode, where the relation between the square root of the drain current and the gate voltage is linear and unaffected by gate-drain bias voltage, the gate of each transistor is connected to its drain [3].

Radiation from beam induced background, striking silicon tracking and vertexing detectors close to the interaction region was found to be a serious problem for SVD detector of the Belle experiment at KEK [4], [5]. The background radiation consists of synchrotron radiation and of particle background, caused by the scattering of beam particles in beam-gas or intra-beam collisions, and amounts in regular operation of the collider to about 1 kGy per year [7]. Since the SVD performance decreases with accumulated dose, mainly due to gain drop of the readout electronics, feedback to the accelerator operation is necessary to maximize its lifetime. Both the instantaneous dose rates and the accumulated doses around the interaction point are being constantly monitored [6]. For the measurement of the total radiation dose p-channel RadFETs [8] were chosen, as the radiation effects in RadFETs are similar to those in the readout electronics itself. Due to space restrictions, 24 bare RadFET chips (Fig. 1)
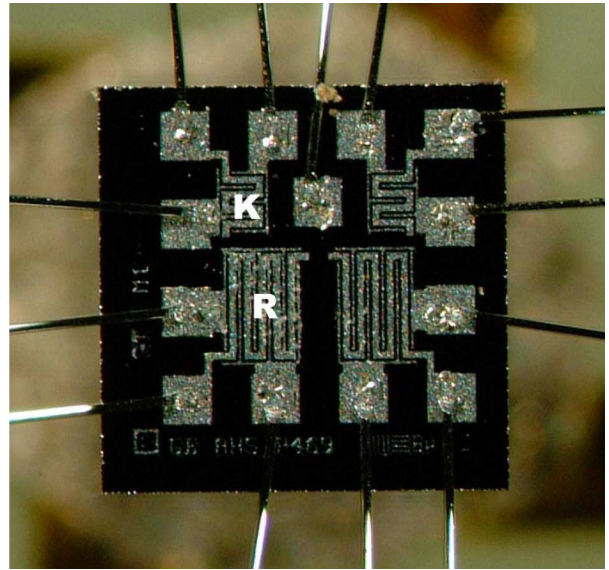

Fig. 1. A mounted RadFET chip used for radiation monitoring in the Belle SVD. It contains 2 transistors with sensitivity in the ~ 10 Gy (K) range (top) and 2 transistors with sensitivity in the ~ 10 mGy (R) range (bottom), which differ in the thickness of the oxide layer [8]. Only the K range transistors are used. The chip dimensions are 1 by 1 by 1 mm^3.

were used. They were placed close to the readout electronics in different layers of the SVD (at 6 azimuthal angles in the innermost layer and at 3 azimuthal angles in the other two layers), both in the forward and the backward direction. Each RadFET chip contains four transistors, two of sensitivity in ~ 10 mGy (R) range and two in ~ 10 Gy (K) range. The physical difference between R and K transistors is the thickness of the oxide layer, which is 0.95 and 0.13 μm, respectively [8]. As it was found that the K transistors operate successfully up to a few 10 kGy [9], which are accumulated doses of interest in our case, only K transistors in each chip are used, for a total of 48 readout channels.

The relation between the gate threshold voltage shift and the dose strongly depends on the production process parameters of the chip and has to be determined experimentally. It was obtained from two types of irradiations with photons from a calibrated ^{60}Co radiation source: "fast", with dose rates of about 0.8 kGy/h and a "slow" one with the rate about 16 Gy/h. For the RadFETs used in Belle, the calibration curve is based on measurements presented in Fig. 2. Gate threshold shift is converted into dose according to the relation $Dose = 0.32\, V_{shift} + 0.12 V_{shift}^2$, where the dose is measured in kGy and the threshold
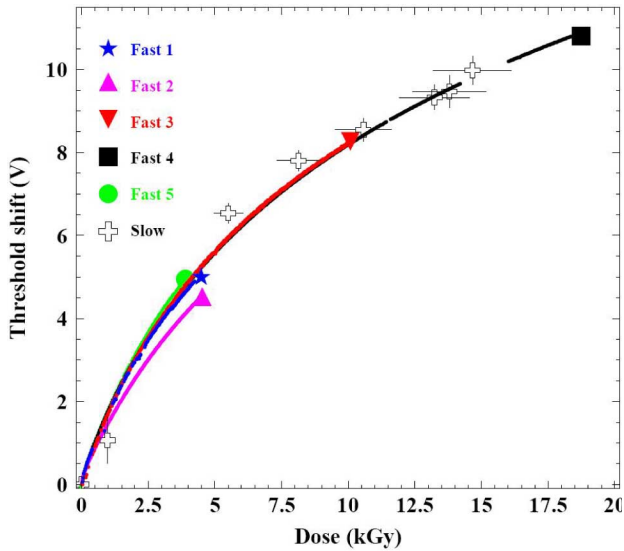
Fig. 2. Threshold shift of a RadFET during irradiation with ^{60}Co source as a function of accumulated radiation dose. There were five "fast" irradiations at ~ 0.8 kGy/h and a "slow" irradiation at ~ 16 Gy/h (denoted by open markers).
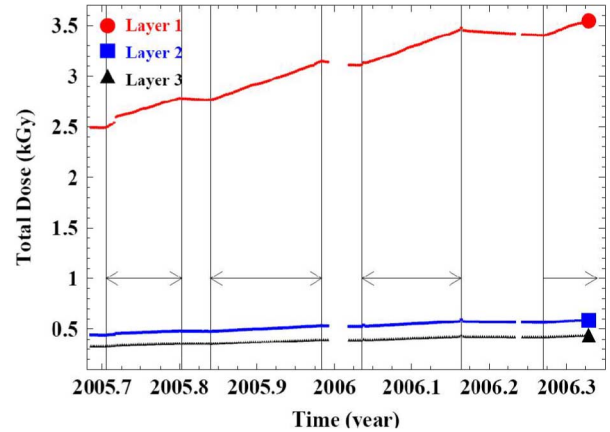

Fig. 3. Time dependence of the average radiation dose in Belle SVD detector since installation of RadFETR modules in 2005. Time intervals with accelerator beams present are denoted by arrows. The seeming decrease of the dose during the maintenance intervals with no beam is due to the RadFET annealing, which is considered offline, and not by the RadFETR. Gaps in the curves are due to power cuts during maintenance periods.

shift in volts. The calibration of the RadFET sensors is presented in detail elsewhere [9].

The new RadFET readout module (RadFETR) has 16 channels and is used to simultaneously monitor 16 different RadFETs by providing a 5.5 ms long constant current pulse of 160 μA to each of them and measuring the corresponding transistor gate threshold voltage. The operating current was chosen so as to minimize the temperature dependence of the RadFET gate voltage [9], which is ~ 0.5 mV/K and small enough for our application. The sampling of a channel itself takes 1.9 ms and is delayed by 1.8 ms from the beginning of the 5.5 ms long current pulse to ensure that the sampling always occurs at exactly the same time for every sample. Except during the constant current pulse, the source and drain of the transistors are electrically shorted. A typical gate threshold voltage of a non-irradiated RadFET used in Belle is 9–10 Volts, and decreases with irradiation. The RadFETs are connected to the modules via four 50 m long shielded 26 wire cables. For radiation monitoring purposes in Belle, three RadFETR modules were installed in August 2005. An example of their performance is shown in Fig. 3 and explained in Section IV.

II. FUNCTIONALITY

A block diagram of a RadFETR is shown in Fig. 4. The 16 channels are being read out sequentially. When a channel is not being sampled, the channel's drain-gate is electrically connected to the positive voltage rail using a CMOS analog switch. The constant current source is generated by using an n-channel MOSFET, an operational amplifier, and a load resistor. Only during the constant current pulse is the CMOS switched open and the gate threshold voltage of the RadFET is sensed by the high impedance input of the first analog buffer amplifier. This amplifier does not contribute to any parasitic current through the RadFET.

After the first analog buffer amplifier, the signals go through two analog multiplexers and are stored in 2.2 μF sampling capacitors. The multiplexers separate the sampling capacitors from the first stage and thus reduce the noise in the secondary readout stage. A set of secondary analog buffer amplifiers is then used to generate the output voltages without draining the potentials of the sampling capacitors. During the entire readout process, digital signals are used to control the timing of the switches and the multiplexers, as implemented using a Xilinx XC95144XL-5TQ144C complex programmable logic device (CPLD) [10].

All RadFETR readout timing is controlled by a CPLD. The CPLD can be re-programmed without opening the module, as the serial I/O connector on the front panel provides the CPLD programming pins. The RadFETR can operate either in a self-triggering mode, with the internal trigger frequency of about 0.5 Hz, or can be triggered externally with frequencies up to 15 Hz. In its operation as a radiation monitoring device for the Belle SVD, the external trigger rate is 0.5–1 Hz, and is set by a data acquisition (DAQ) logger [11]. The trigger rates of this order are sufficient, as the RadFET themselves do not produce fast signals when exposed to radiation.

As the RadFETR modules are primarily intended for use in Belle, a double-width NIM module (Fig. 5) was chosen as a mechanically convenient form factor. During operation, a RadFETR module draws about 500 mA of current at +12 V DC from a standard NIM bin power supply. For the sake of portability, for instance needed at a ^{60}Co irradiation facility, the module can also be operated as a stand alone device, and powered through a +12 V DC socket on its front panel.

III. TYPES OF READOUT OUTPUT

A RadFETR module has three different types of outputs for the measured gate threshold voltages. The first one, "Parallel Analog Output" (PAO), continuously provides the gate threshold voltages of all channels, and is connected to a 34-pin data logger output connector on the front panel. Each of the 16 output channels is paired with a common ground line. This output is used for data taking in Belle. All the outputs are
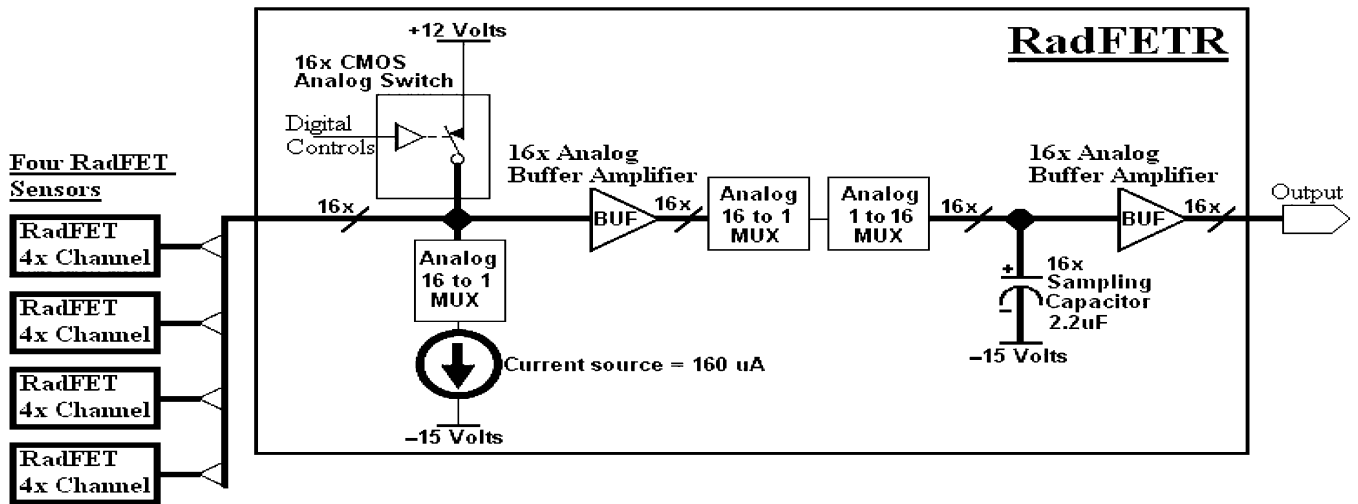
Fig. 4. Block diagram of the RadFETR. The 16 input channels on the left are connected to different RadFET sensors. A single constant current source is multiplexed to all the channels, and the gate threshold voltages are sensed by the first stage analog buffer amplifiers. Sampling capacitors and the final stage readout on the right are separated from the first stage by a pair of analog multiplexers to reduce the noise in the read-out.
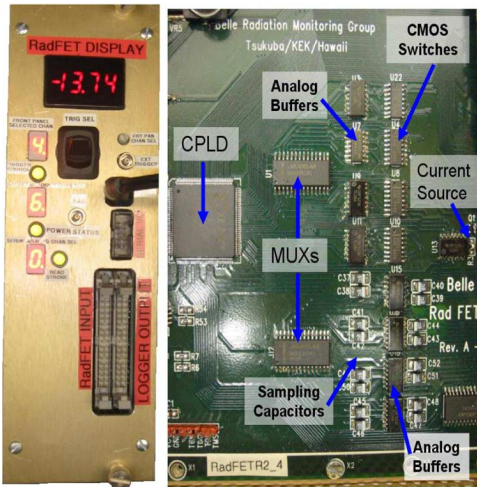

Fig. 5. Front panel of an operating RadFETR double NIM module (left), containing a digital display, readout channel number indicators, serial I/O and parallel output connectors, a trigger select switch and the input connector for the RadFETs. The digital display shows the gate threshold voltage of the selected channel. The RadFETR circuit board is shown on the right. The different discrete ICs being used are described with labels for this photograph.
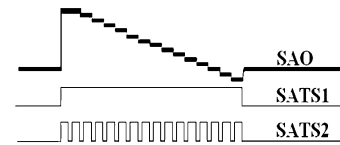

Fig. 6. Timing diagram of the serial readout of the RadFETR. SAO is an analog signal that is serialized from the 16 output channels of the RadFETR. SATS1 is a digital signal that is an enable signal for the serial readout. SATS2 is a serial clock signal.

simultaneously digitized by a multi-channel data logger [11] and stored to a computer.

The second one, "Front Analog Output" (FAO), displays the measured value of a single, selectable channel on the built-in digital display and provides the signal on a front panel lemo connector. The channel is selected by a rotary switch. This output is used for monitoring system set-up and oscilloscope testing, as well as during portable applications.

The third, "Serial Analog Output" (SAO) provides the information from all 16 channels serialized into a single time-multiplexed output signal, and two digital timing signals (SATS1 and SATS2) needed for initiating analog conversion in a generic data logging module. An example of the timing diagram is shown in Fig. 6. SATS1 in the high state indicates that the serial output is active. SATS2 can be used to initiate an analog conversion

cycle, synchronous to the sequential selection of the PAO channels. This readout scheme allows for compact readout of a larger number of RadFET channels in the future.

IV. SYSTEM PERFORMANCE

During the read-out phase, the 160 μA constant current source is connected for 5.5 ms to the RadFET and its threshold gate voltage is read out by the first stage analog buffer amplifier. For system stability and reliability it is essential that the current does not change in the case of different RadFET gate threshold voltages. The stability of the constant current source was tested using a number of different resistive loads, connected between V_{CC} (+12 Volts) and the readout channel under investigation. The dependence of the output voltage in Volts on the connected resistive load in kOhm is shown in Fig. 7, its slope corresponds to the current in mA. A linear fit to the measured points yields $V_{gate}(R) = (-0.1589 \pm 0.0003)R + (12.029 \pm 0.019)$, indicating that the error due to non-linearity of the constant current source is negligible.

In the process of commissioning, three tests were performed to confirm the level of RadFETR readout noise. The first and second test used data from the PAO. All 16 channels were simultaneously read out every two seconds and logged by a PC, using a computer generated triggering signal. In the first case, resistive loads were connected to the RadFETR inputs, and in the second case, actual irradiated RadFETs were used. A third test investigated the serialized analog signal from SAO, using the same
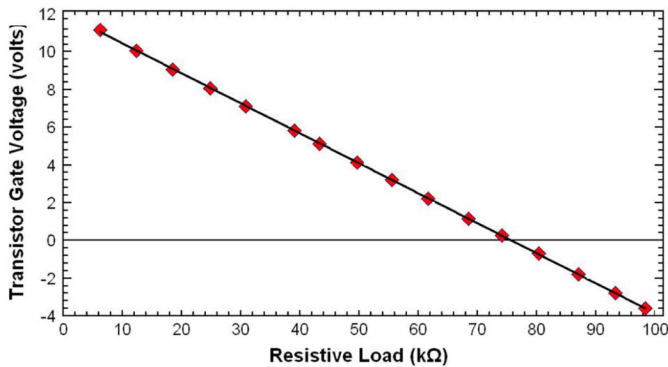
Fig. 7. Plot of the transistor gate voltage versus the resistive test load. A linear fit to the data was made to show the linearity and error for the current source. The slope is consistent with a current source of 160 μA.
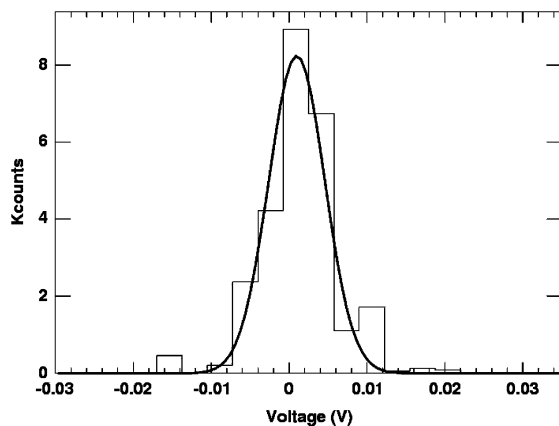

Fig. 8. An example of the noise distribution in a randomly selected read-out channel of the serial analog output (SAO). In this case, Gaussian fit to the distribution yields a noise level of 5 mV. Such a measurement was done for every channel for each of the three performance tests.

resistive loads as in the first test. The SAO signal was de-serialized using SATS1 and SATS2 digital signals provided from an external data acquisition module and then logged by a PC in the same way as in tests 1 and 2. The data acquisition was performed using two commercial USB-based 8-channel DAQ modules (USB-1208FS) [12]. An example of the signal distribution for about 26000 consecutive readings of a particular channel is given in Fig. 8. A Gaussian fit to the distributions for the three tests described yields noise levels of 3.76 mV, 4.76 mV and 6.26 mV, respectively. These noise levels are the mean of the 16 individual channel fits. The higher noise level in the case of SAO is likely due to the passage of the analog signal through an additional analog multiplexer during the serialization process.

The performance of the RadFETR modules installed in Belle is shown in plots of the average accumulated doses in Rad-FETs at each SVD layer versus time (Fig. 3). During operation,

the data are being read out approximately once per minute and stored to a computer. All the data is kept indefinitely. The monitoring system was operational throughout the accelerator beam time, with some interruptions due to the power cuts during maintenance periods. A seeming decrease in the total dose during these periods is due to the RadFET annealing. The annealing effects are not dealt with by the RadFETR module itself, but can be accounted for by an offline by re-processing of the data.

V. CONCLUSION

In summer 2005, three RadFETR modules were successfully commissioned and implemented as the RadFET sensor readout for the Belle SVD radiation monitoring system. During commissioning, constant current sources of the new reader modules were found to be stable for the entire range of possible loads that may be encountered when reading out an irradiated RadFET sensor. The spread of both parallel and serial output signals due to the read-out electronics was measured to be on the order of 5 mV. This is less than a percent of the signal up to an accumulated dose of about 15 kGy, which is the radiation hardness limit of the Belle SVD readout electronics. The RadFETR device is thus suitable for radiation monitoring of the Belle SVD throughout its expected lifetime. Since installation, RadFETR modules have been operating reliably and without interruptions throughout beam operation.

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