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High-rate timing resistive plate chambers with ceramic electrodes

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ABSTRACT

We describe recent advances in developing radiation-hard ceramic resistive plate chambers (CRPCs) with Si_3N_4/SiC composites. Bulk resistivity measurements for this material for different manufacturing processes are reported. The results show that the bulk resistivity ρ can vary between 10^7 and 10^{13} Ω cm. The varistor type behaviour of the material is analysed. A comparison with other materials used in timing RPCs is given. We describe the assembly and tests of CRPC prototypes in electron and proton beams. For a prototype with $\rho \sim 5 \times 10^9$ Ω cm, the efficiency of the detectors is 95% at a flux of 2×10^5 cm^{-2} s^{-1}. The time resolution at the same flux is about 120 ps. A prototype with $\rho \sim 2 \times 10^{10}$ Ω cm shows an efficiency of about 85% up to fluxes of 5×10^4 cm^{-2} s^{-1} with a time resolution better than 80 ps. The results are compared with RPC models.

1. Introduction

Resistive Plate Chambers (RPCs) have been widely used for time-of-flight (ToF) measurements in particle and nuclear physics experiments. Experiments like FOPI [1], HADES [2], HARP [3], ALICE [4] or STAR [5] have successfully used RPCs during their operation. Soda-lime glass has been the predominant material in timing RPC electrodes for many years. Its affordability, easy manufacturing and availability have been its main advantages. However, RPCs with glass electrodes have limited rate capabilities (up to a few hundred particles/cm^2 s) due to the glass high bulk resistivity of $\rho \sim 10^{13}$ Ω cm. The Compressed Baryonic Matter (CBM) experiment at FAIR, will use a detector equipped with RPCs to measure the time-of-flight of particles produced in heavy-ion collisions. The large particle rates expected at the Time-of-Flight Wall [6] have motivated the research and development of new materials capable of withstanding these fluxes. Some possibilities to achieve these fluxes have been developed. Semiconductor-doped glass [7,8], warm soda-lime glass [9] or ceramics [10,11] are among these possibilities. High-rate timing RPCs will not only be of use in the CBM experiment but also in any other environment where good time resolution and efficiency as well as large areas are needed. Therefore, investigation of new materials is an important step to enable future particle and nuclear physics experiments.

2. Si_3N_4/SiC material

The use of ceramics as electrode materials was investigated in the last decade [12,13] with promising results. The Si_3N_4/SiC composites used at HZDR for timing RPCs have been developed in collaboration with Fraunhofer Institute for Ceramic Technologies (IKTS). Si_3N_4 is an insulator material with bulk resistivity of about 10^{14} Ω cm. SiC is a semiconductor material with bulk resistivity 10^4 Ω cm. Adding the SiC component to a Si_3N_4 material modifies the bulk resistivity of the mixture due to percolation paths [14]. The bulk resistivity of the composites can be tuned in the range of 10^7–10^{13} Ω cm through the manufacturing process.

The bulk resistivity goal for implementing these ceramic composites in high-rate timing RPCs is about 10^9–10^{10} Ω cm. A quality assurance process was established to ensure that the quality of the plates and their physical parameters are adequate for their use. In the following sections, the measured parameters of these materials are discussed and compared with other available RPC electrode materials.

2.1. Bulk resistivity

The bulk resistivity of Si_3N_4/SiC plates was measured in a dedicated set-up. A Kethley 485 picoammeter is used to measure the current flowing through the ceramics when a voltage different is applied between both sides of the plate. The picoammeter can supply up to 1000 V and has a current precision of 0.1 pA. The set-up is controlled with a laptop equipped with Labview supplied by the picoammeter manufacturer. In cases where a higher voltage is desired, an external power supply can be used. Each measured

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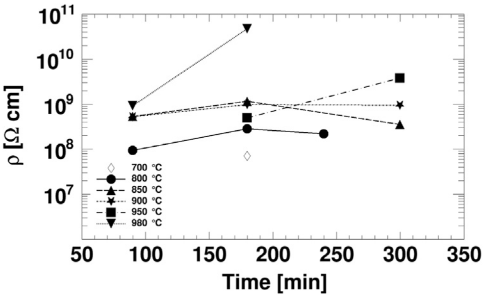

Fig. 1. Bulk resistivity of ceramic plates with equal Si_3N_4/SiC composition ratios but different manufacturing processes quantified by the sintering temperature given in the legend and for various sintering times.

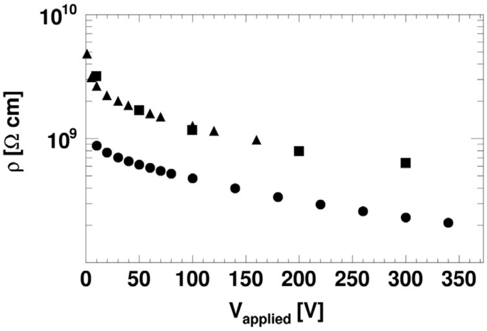

Fig. 2. The bulk resistivity as a function of the applied voltage for three probes. A test plate, used for calibration, is represented by ▲, plate #7 by ● and plate #10 by ■.

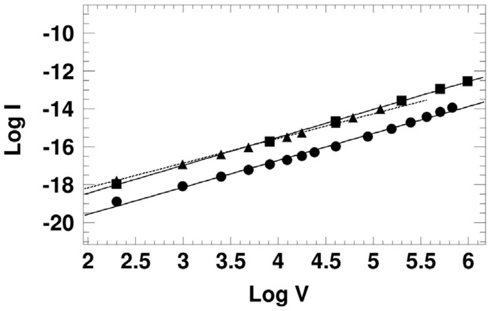

Fig. 3. Ln I as a function of Ln V for three varistor-type Si_3N_4/SiC ceramic samples (▲: test plate, ●: plate # 7, ■: #10).

Table 1
Comparison of materials used as RPC electrodes. Semiconductive glass data extracted from Ref. [8]. Soda-lime glass data obtained from [22].

Material	Thickness (mm)	ρ (Ω cm)	ϵ_r	tan δ	ΔT
Si_3N_4/SiC	2	10^{7}–10^{13}	12	0.033	25–49
Sem. glass	0.7	10^{10}–10^{11}	6	0.025	25
Soda-lime	0.3	10^{13}	5.8	0.025	25

point corresponds to the average current flowing through the ceramic plate during a period of ten minutes. The measurement electrode has an active area of 0.965 cm^2. The bulk resistivity is calculated as

$$\rho = R\frac{S}{d} = \frac{V\,S}{I\,d} \tag{1}$$

where $R = V/I$ is the resistance of the volume in which the current I is flowing. V is the voltage applied, S is the measuring electrode area and d is the plate thickness.

The bulk resistivity of several plates with the same composition ratios but different manufacturing processes was measured. In particular, the sintering duration and temperature were modified. Sintering is a step during the ceramic manufacturing process where the material is subjected to high temperatures for a specified time. During this process, the ceramics achieve the final bonding stage. This process also helps to eliminate organic impurities added to the material during the manufacturing process. The results for these measurements are shown in Fig. 1.

The wide combination of temperatures and times shows how the bulk resistivity can be tuned. The bulk resistivity does not seem to be strongly dependent on the sintering time for low temperatures. For $T = 950$ °C and $T = 980$ °C, however, the bulk resistivity shows a high increase with the time. This is due to the physical processes occurring inside the material during sintering.

Si_3N_4/SiC composites exhibit a varistor-type behaviour. This implies a variation of the bulk resistivity with the voltage difference applied to both sides of the material. The bulk resistivity as a function of the potential difference is plotted in Fig. 2. The bulk resistivity decreases by almost an order of magnitude over the considered voltage range. In comparison, semiconductor-doped glass experiences a decrease of 20% up to 1000 V [15].

Another way to test this behaviour is to study the current-voltage (I–U) dependency. A resistive material following exclusively Ohm's Law shows a linear I–U behaviour. However in a varistor material, the current has a dependence $I/I_0 = U^{\kappa}$ where I_0 is the current flowing through the sample when the potential difference is one Volt between both sides. Thus, the logarithm of the current has a linear dependence with the logarithm of the voltage. This is displayed in Fig. 3. A fit to this data allows us to extract the parameter κ as

$$Ln\, I - Ln\, I_0 = \kappa\, Ln\, U \tag{2}$$

The parameter κ was extracted from these measurements giving an average over the three plates of $\kappa = 1.381596 \pm 0.00011$. This implies that the dependence of the bulk resistivity on the voltage is independent of the plate, and therefore is intrinsic to the material composition. The only difference between samples is the absolute value of the bulk resistivity taken at the same voltage ($V = 100$) and room temperature ($T = 22$ °C).

2.2. Radiation hardness

The electrode material in RPCs must be resistant against radiation effects to ensure the long term operation of the detectors in high radiation environments. Three plates were irradiated at FRM-II (München). The neutron fluence was 10^{13} n_{eq} cm^{-2} in the MEDAPP channel. The continuous neutron spectrum spawns from 0.1 to 10 MeV. The bulk resistivity after irradiation is 60% the bulk resistivity before irradiation.

2.3. Comparison with other electrode materials

In the process of developing high-rate RPCs, other materials have been considered. Semiconductor-doped glass developed at Tsinghua University [8] has been selected as the material for the low polar angle regions of the CBM ToF Wall corresponding to particle fluxes up to 25×10^{3} cm^{-2} s^{-1}. The large polar angles will be equipped with soda-lime glass RPCs.

A comparison of the glass materials with ceramics is given in Table 1. The thickness of electrodes made of different materials is currently limited by technical reasons. The bulk resistivity of ceramics can achieve lower values than the semiconductor-doped glass and therefore, ceramic RPCs can operate at higher particle fluxes. The electrical parameters like the electrical permittivity and the tangent loss, tan δ, provide information about the signal induction and degradation when transmitted along the read-out