

Improved Techniques for the Fabrication of Frisch Collar CdZnTe Gamma Ray Spectrometers

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Abstract—New methods, designed for the commercial-scale production of Frisch collar CdZnTe gamma ray spectrometers, are described in detail in the following work. Past methods required considerable skilled labor, were not readily automatable, and batch processing was only supported through a portion of the fabrication process. Advances in dielectric materials technology allow for new processes that readily apply the required dielectric film between the CdZnTe crystal and the conductive collar. The processes use spray or chemical vapor deposition methods to accurately achieve a specific thickness. Furthermore, application of the conductive collar was improved to facilitate commercial manufacturing. Comparisons in device performance are presented between the previous and new methods to illustrate the effectiveness and robustness of the new fabrication method. Parylene N performed well as the dielectric layer, while nickel-based paint, high-purity silver-based paint, and a silver-suspension Electrodag all performed well as the conductive layer, each maintaining spectral performance.

Index Terms—CdZnTE, gamma-ray spectroscopy detectors.

I. INTRODUCTION

CADMIUM ZINC TELLURIDE (CdZnTe) Frisch collar spectrometers have shown great promise as room temperature operated devices that can provide sub-1% FWHM energy resolution at 662 keV as seen in Fig. 1. Despite this outstanding performance, the fabrication of Frisch collar devices, specifically the application of the dielectric Teflon layer and the conductive copper collar, is labor-intensive and susceptible to error. Ideally, the method of fabrication should be automatable and scaleable to mass production quantities.

Frisch collar devices are typically constructed by wrapping a bar detector with common Teflon tape ($\sim 150 \mu\text{m}$ thick) and a copper shim, which is then grounded to the cathode. The thickness of the dielectric layer is an important parameter to the success of constructing a Frisch collar, as it determines to what extent the weighting field and electric field are affected by the conductive Frisch collar. Unfortunately, the current method allows for little freedom in varying the thickness of the dielectric layer, thus optimizing device performance is difficult. Similarly, the

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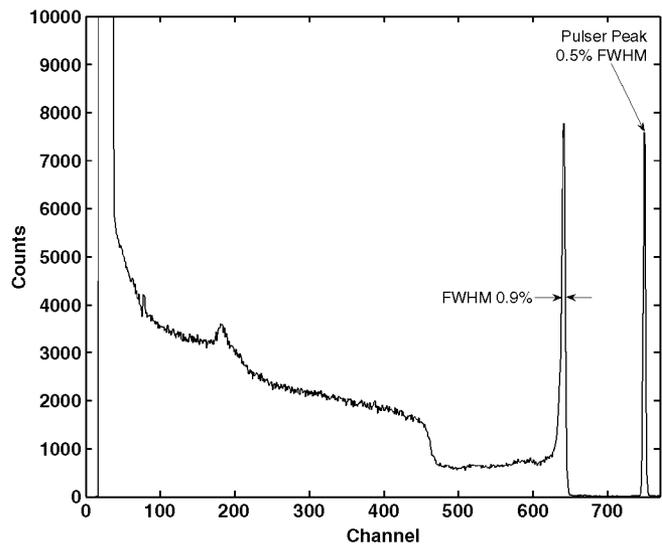


Fig. 1. Sub-1% FWHM at 662keV spectrum experimentally measured with a $5 \times 5 \times 10 \text{ mm}^3$ Frisch collar device. No electronic corrections were used. Applied bias is 1140 V.

conductive collar shape and location plays an important role in determining the weighting and electric fields. An air gap between the copper shim and the dielectric layer can dramatically affect the performance of the devices as can the location of the end of the collar [1].

Two new methods of applying the dielectric layer were developed and tested against the standard procedure in an effort to improve fabrication yield and decrease production time. The first method takes advantage of new fluoropolymers to apply the dielectric layer by spraying or dipping. Film thicknesses can be controlled to precise dimensions by varying the viscosity of the fluoropolymer with a perfluorinated solvent. The second dielectric application method utilizes a vapor deposition process in which parylene is deposited uniformly over the device to a specified thickness. Parylene is an organic polymer with a low dielectric constant developed by the Union Carbide Corporation. Parylene can be coated on the surfaces of the CdZnTe device at room temperature in vacuum through a vapor deposition process. Parylene is an excellent moisture barrier that encapsulates the object and yields conformal and pin-hole free films [2].

Three new methods of applying a conductive collar were also tested for performance. Nickel-based and silver-based paints were both tested for compatibility with the dielectric layers as was silver-suspension Electrodag (Silverdag).

In all, four different Frisch collar preparation processes were developed and tested against the standard method originally described in detail in [1]. The techniques utilized and their results are presented in the following sections.

II. THEORETICAL CONSIDERATIONS

The weighting potential within a Frisch collar device is found by numerically solving the Laplace equation,

$$\nabla(\epsilon_r \epsilon_0 \nabla V_w) = 0, \quad (1)$$

where V_w is the weighting potential at a location inside the Frisch collar device, ϵ_r is the relative permittivity of the material as a function of location and ϵ_0 is the dielectric permittivity of vacuum. Boundary conditions for the weighting potential are such that the collecting electrode potential is held at unity while all other electrodes are grounded (zero).

The operating voltage potential within a Frisch collar device, on the other hand, is found using Poisson's equation,

$$\nabla(\epsilon_r \epsilon_0 \nabla V) = -\rho, \quad (2)$$

in which V is the voltage potential and ρ is space charge density. Here, the electrodes are all set equal to their respective applied bias potential when setting boundary conditions. The following calculations assume zero space charge.

Two competing mechanisms exist within the Frisch collar device. On one hand, a strongly nonlinear weighting field is advantageous in that signal induction due to hole transport is minimized. Conversely, a strongly nonlinear electric field results in poor charge transport near the cathode where the electric field is very weak. This fact indicates that an optimal dielectric thickness exists for a given CdZnTe crystal size and dielectric layer properties. Ideally, a fabrication process capable of fine control of dielectric layer thickness would permit experimentally locating such an optimum.

A thinner dielectric layer permits the conductive Frisch collar to affect the weighting potential within the device to a higher degree, which in turn decreases the importance of hole transport during signal induction. Fig. 2 illustrates this point. The curves in Fig. 2 are the calculated weighting potentials as a function of distance from the cathode along the center line of a $5 \times 5 \times 10 \text{ mm}^3$ Frisch collar device with insulator layer thicknesses t . Calculated weighting and voltage potentials were found using the commercial software package, COULOMB, for the full three dimensional geometry [3].

The dielectric permittivity of the insulating layer is of utmost importance in selecting a suitable substitute because it, like dielectric thickness, determines to what extent the weighting potential is affected by the conductive collar. Fig. 3 is a plot of weighting potentials calculated along a line through the center of a $5 \times 5 \times 10 \text{ mm}^3$ Frisch collar device with $500 \mu\text{m}$ dielectric layers of different dielectric constants ϵ_r .

Thin coatings require the dielectric material to possess high resistivity and sufficient dielectric strength. Near the anode, the thin dielectric films, on the order of $100\text{--}500 \mu\text{m}$ thick, must

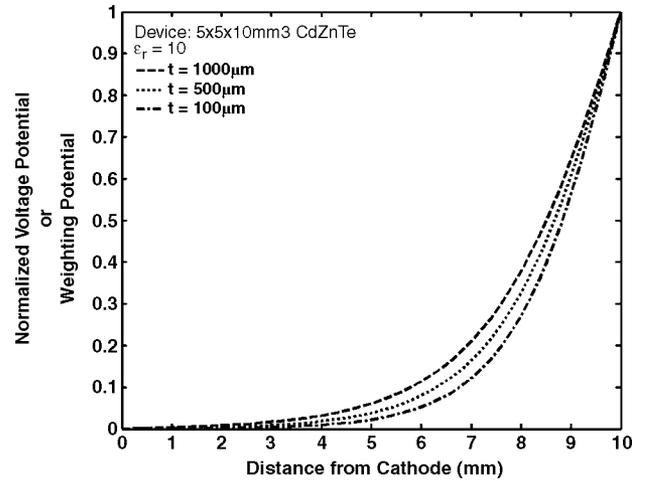


Fig. 2. Calculated weighting potentials/normalized voltage potentials along a line centered along the length of a $5 \times 5 \times 10 \text{ mm}^3$ CdZnTe Frisch collar device found by numerically solving the Laplace equation for three different thicknesses of insulator.

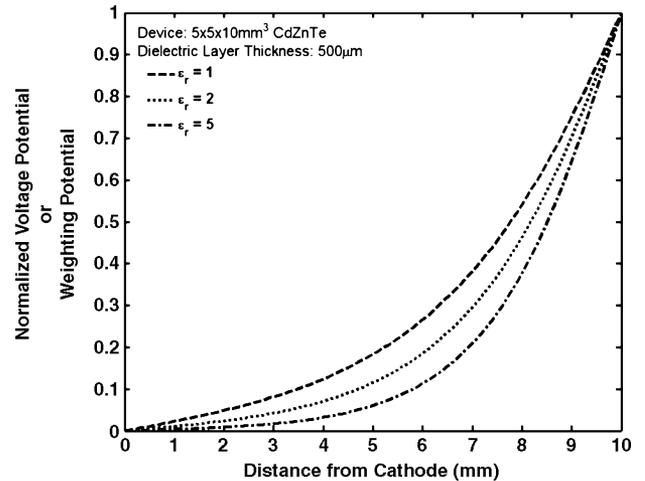


Fig. 3. Plot of calculated weighting potentials/normalized voltage potential distributions illustrating the effect of insulating layer dielectric constant on potential distribution.

withstand electric fields on the order of 10^5 V/cm assuming the anode and Frisch collar are directly opposite one another.

Two potential candidate dielectric materials were considered. The first, DuPont's Teflon AF, is a liquid version of Teflon that can be cured at room temperature. The liquid form allows deposition to be done a number of ways, such as spraying, dipping or brushing. Further, the viscosity of Teflon AF can be adjusted using 3M's FC-72 Fluorinert solvent, thus allowing layer thicknesses to be adjusted as needed. Initial trials with Teflon AF showed that dipping and brushing were inadequate methods. Uniformity of the Teflon AF coating was limited by surface tension when applied via dipping. Similarly, brushing the Teflon AF onto the CdZnTe surfaces produced irregular layers of widely varying thickness. From these initial tests, spraying a dilute mixture of Teflon AF in FC-72 solvent was determined to be the best method for applying uniform coatings.

The second material considered for use as a Frisch collar dielectric layer was Parylene. Parylene is commercially available in many variants. Those considered for this application included

TABLE I
ELECTRICAL PROPERTIES OF DIELECTRIC MATERIALS CONSIDERED

Material	Dielectric Constant ^c	Resistivity ($\Omega\cdot\text{cm}$)	Dielectric Strength (kV/mm)
Teflon AF ^a	1.93	$>1\times 10^{17}$	19
Parylene C ^b	2.95	8.8×10^{16}	220
Parylene D ^b	2.80	1.2×10^{17}	217
Parylene N ^b	2.65	1.4×10^{17}	276

a. Properties reported in [4].

b. Properties reported in [5].

c. Measured at 1 MHz.

Parylene N, C, and D. While Parylene C was initially tested, Parylene N was determined to be the optimum choice among the commercially available options as it possesses higher resistivity and higher breakdown strength than the other two options. Table I compares the electrical properties of Teflon AF with those of the three Parylene variants considered.

Parylene is synthesized and deposited in three main steps. Initially, the dimers are thermally vaporized (sublimated) and then pyrolyzed into the vapor phase monomers; subsequently the monomers are condensed and polymerized at the molecular level at room temperature on the substrate. The Parylene deposition system, a Specialty Coating Systems PDS 2010 LABCOTER 2, uses the following process parameters for deposition of Parylene N [6]. The vaporization (sublimation) of the dimers occurs at 160 °C under a pressure of 0.1 Torr in the vaporizer. At this stage, the dimers are sublimated into the vapor phase and enter into the pyrolysis furnace at 650 °C and 0.5 Torr. The dimers in the gaseous form are then pyrolyzed into monomers in the pyrolysis furnace. Finally, polymerization of the monomers occurs in the deposition chamber at room temperature and 0.05 Torr. The Parylene deposits as the polymer forms from vapor phase monomers onto the substrate.

III. EXPERIMENTAL PROCEDURE

A. Teflon AF

A CdZnTe bar detector, Detector 1, was first fabricated from Redlen Technologies material as per the process described in [7]. Gold wires were then bonded to the electrodes using silver epoxy. A ^{137}Cs spectrum was recorded for this planar configuration.

A Frisch collar was constructed around the bar detector by wrapping the crystal with Teflon tape to a thickness of $\sim 150\ \mu\text{m}$, followed by a copper shim. A ^{137}Cs spectrum was again recorded to provide a base performance to compare against. The copper Frisch collar and the Teflon tape were then removed.

The lateral sides were spray-coated with a solution of DuPont's Teflon AF dissolved in 3M's FC-72 Fluorinert perfluorinated solvent. A thin layer, measured to be $100 \pm 10\ \mu\text{m}$ thick by a digital caliper, was applied and allowed to dry at room temperature for 12 hours. At this point in the process, the detector was a planar device with gold contacts at each end and a layer of Teflon AF on the lateral sides.

A copper Frisch collar was next wrapped around the sides of the device and tested for spectral performance. A third ^{137}Cs

spectrum was recorded. The spectrum confirmed that the device was indeed performing as a Frisch collar device.

The copper Frisch collar was removed, a mask was placed over each electrode and a conductive nickel-based paint was sprayed onto the lateral sides to act as the Frisch collar. The paint was allowed to dry at room temperature for 1 hour and a ^{137}Cs spectrum was recorded.

The nickel-based paint was then removed using acetone and a copper Frisch collar reapplied. A final ^{137}Cs spectrum was recorded for Detector 1.

B. Parylene N

Three CdZnTe devices (Detectors 2, 3 and 4) were fabricated from Redlen Technologies material again as per the process described in [7]. Electroless gold contacts were applied to the ends of the crystals and gold wires bonded to the contacts using a silver epoxy. Each device was tested for ^{137}Cs spectral performance in this planar configuration as well as with a Frisch collar fabricated from Teflon tape and copper shim.

Next, Detectors 2 through 4 were placed within the deposition chamber of the parylene deposition system. In order to have a uniform exposure to the deposition chamber atmosphere, the devices were suspended from the gold wires attached to device contacts. Parylene N was simultaneously deposited on the three devices for 13.5 hours. Approximately 48.7 g of dimer material was consumed in the process and produced a film $170 \pm 5\ \mu\text{m}$ thick on Detector 2 and $150 \pm 5\ \mu\text{m}$ thick on Detectors 3 and 4. All thicknesses were measured by a scanning electron microscope (SEM). After deposition, the Parylene N coated devices were each wrapped with copper shim and a ^{137}Cs spectrum recorded.

In the final step, the copper Frisch collars were removed and conductive collars were applied to the detectors' lateral surfaces to act as the Frisch collars. Detector 2 had a nickel-based paint applied, while a silver-based paint was applied to Detector 3. Lastly, Detector 4 used a layer of Silverdag as the conductive Frisch collar. A final ^{137}Cs spectrum was recorded for each detector.

IV. RESULTS

A. Teflon AF

The spectra plotted in Fig. 4 are a comparison of the spectral performance of Detector 1 wrapped in Teflon and copper shim against Teflon AF wrapped in copper shim. Energy resolution was noted as degrading from $2.4 \pm 0.2\%$ FWHM to $2.8 \pm 0.2\%$ FWHM at 662 keV when the Teflon tape was replaced by Teflon AF.

Fig. 5 plots the spectra obtained when the copper shim Frisch collar was removed and replaced with a nickel-based paint. Energy resolution degraded slightly from $2.4 \pm 0.2\%$ FWHM to $2.8 \pm 0.2\%$ FWHM at 662 keV and significant amounts of noise were noted in the spectrum when using the Teflon AF/Ni combination.

Finally, Fig. 6 compares the performance of Detector 1 with the Teflon AF/Cu shim configuration for the Frisch collar before and after the nickel-based paint was applied and removed. The first spectrum was obtained prior to applying the nickel-based

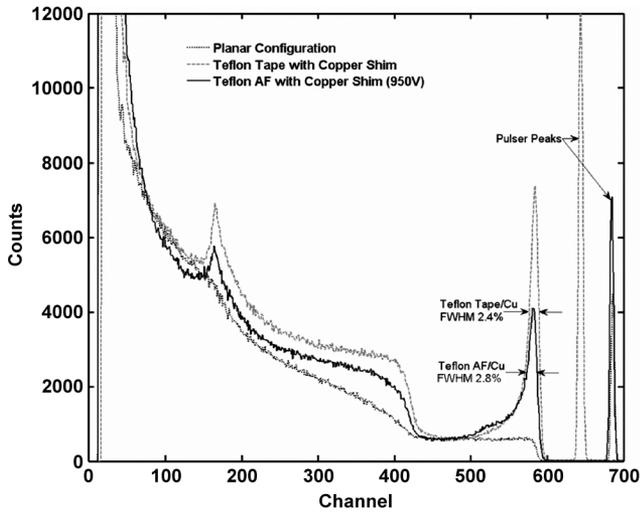


Fig. 4. Pulse height spectra of Detector 1 ($4.3 \times 4.7 \times 8.3 \text{ mm}^3$) comparing the planar configuration, the original Teflon tape and copper shim fabrication method and the Teflon AF with copper shim spectra. Applied bias was 1000 V, unless specified.

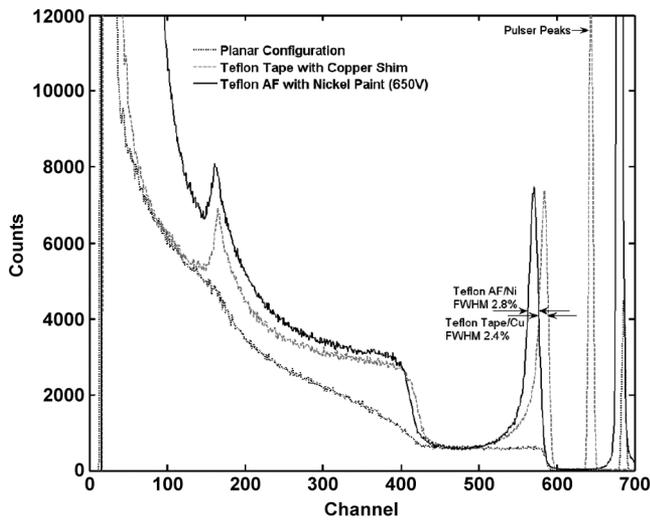


Fig. 5. Pulse height spectra of Detector 1 ($4.3 \times 4.7 \times 8.3 \text{ mm}^3$) comparing the spectrum obtained with the standard Teflon tape and copper shim fabrication method and the spectrum obtained when the Frisch collar was fabricated with Teflon AF and a nickel-based paint. Applied bias was 1000 V, unless specified.

paint. The second spectrum was collected after the nickel-based paint had been removed. Although energy resolution improved from $2.8 \pm 0.2\%$ FWHM to $2.6 \pm 0.2\%$ FWHM at 662 keV, system noise remained high in the lower channels.

B. Parylene N

Figs. 7 and 8 are a comparison of the various configurations of Detector 2. In Detector 2, Parylene N was used as the dielectric layer and nickel-based paint was used as the conductive Frisch collar. Energy resolution degraded from $2.6 \pm 0.2\%$ FWHM to $3.3 \pm 0.2\%$ FWHM at 662 keV when the Teflon tape/Cu shim combination was replaced by the Parylene N/Cu shim combination. Nonetheless, energy resolution improved from $2.6 \pm 0.2\%$ FWHM to $2.1 \pm 0.2\%$ FWHM at 662 keV when the Teflon

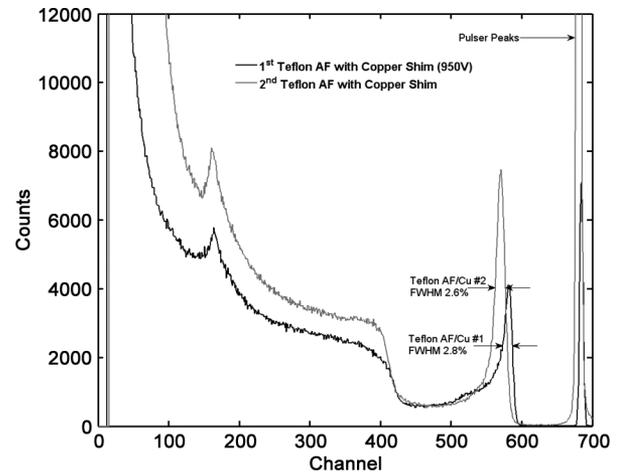


Fig. 6. Pulse height spectra of Detector 1 ($4.3 \times 4.7 \times 8.3 \text{ mm}^3$) comparing the responses before and after the Ni-based paint was applied and removed. Applied bias was 1000 V, unless specified.

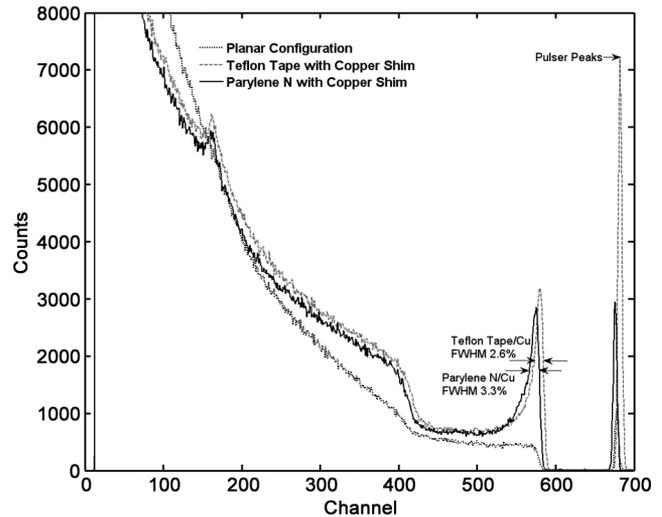


Fig. 7. Pulse height spectra of Detector 2 ($4.64 \times 4.79 \times 8.71 \text{ mm}^3$) comparing the standard Teflon tape and copper shim Frisch collar to the Frisch collar fabricated with Parylene N and copper shim. Applied bias was 1000 V.

tape/Cu shim arrangement was replaced with a Parylene N/Ni-based paint combination.

Figs. 9 and 10 are a comparison of the spectra obtained with Detector 3. Detector 3 used a Ag-based paint as the conductive Frisch collar rather than the Ni-based paint used for Detector 2. Energy resolution was again observed to degrade from $1.8 \pm 0.2\%$ FWHM to $2.3 \pm 0.2\%$ FWHM at 662 keV when the Teflon tape/Cu shim combination was replaced by the Parylene N/Cu shim combination as shown in Fig. 9. Fig. 10, however, shows little change in energy resolution between the Parylene N/Ag-based paint and Teflon tape/Cu shim fabrications.

The comparisons between the spectral performances of the Frisch collar configurations of Detector 4 are shown in Figs. 11 and 12. Fig. 11 shows the energy resolution degraded from $1.9 \pm 0.2\%$ FWHM to $2.3 \pm 0.2\%$ FWHM at 662 keV when Teflon tape was replaced by Parylene N. This result is similar to that obtained for Detector 3 in Fig. 9. Fig. 10, on the other hand, shows that replacing the Teflon tape/Cu shim fabrication with

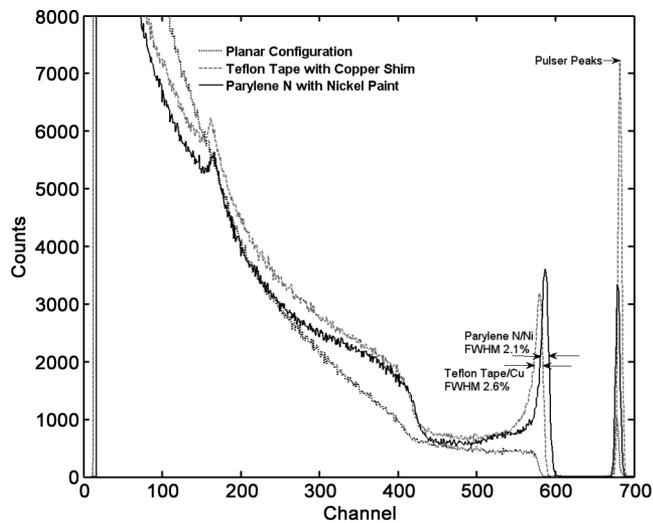


Fig. 8. Pulse height spectra of Detector 2 ($4.64 \times 4.79 \times 8.71 \text{ mm}^3$) comparing the standard Teflon tape and copper shim Frisch collar to the Frisch collar fabricated with Parylene N and nickel-based paint. Applied bias was 1000 V.

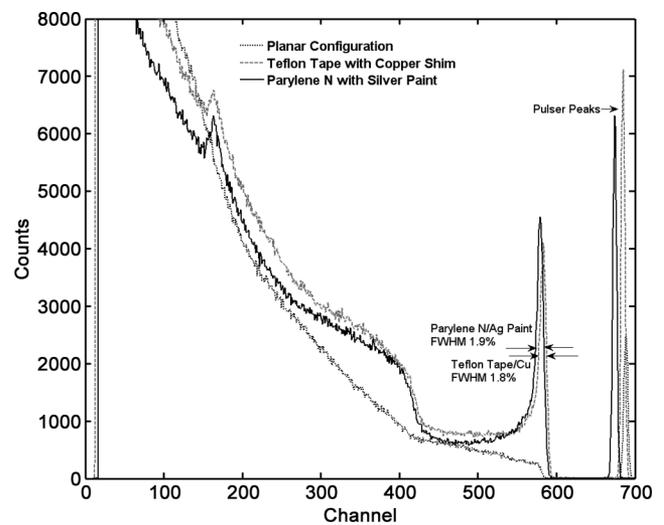


Fig. 10. Pulse height spectra of Detector 3 ($4.83 \times 4.61 \times 8.92 \text{ mm}^3$) comparing the standard Teflon tape and copper shim Frisch collar to the Frisch collar fabricated with Parylene N and silver-based paint. Applied bias was 1000 V, unless specified.

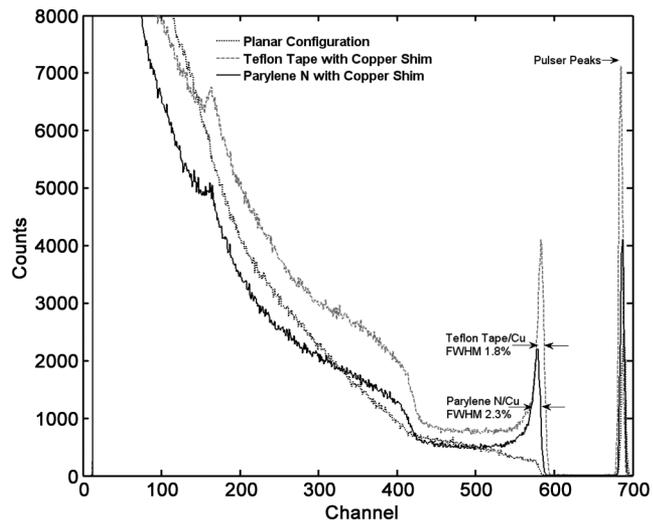


Fig. 9. Pulse height spectra of Detector 3 ($4.83 \times 4.61 \times 8.92 \text{ mm}^3$) comparing the standard Teflon tape and copper shim Frisch collar to the Frisch collar fabricated with Parylene N and copper shim. No additional noise was noticed. Applied bias was 1000 V, unless specified.

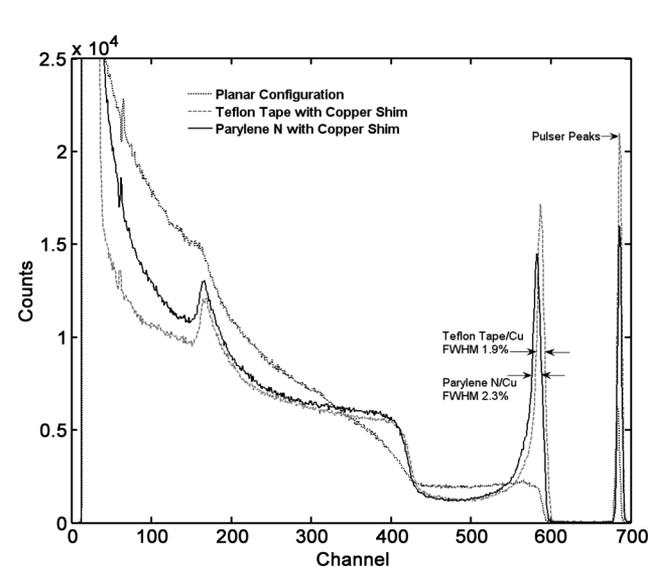


Fig. 11. Pulse height spectra of Detector 4 ($4.40 \times 4.75 \times 9.10 \text{ mm}^3$) comparing the standard Teflon tape and copper shim Frisch collar to the Frisch collar fabricated with Parylene N and copper shim. Applied bias was 1000 V.

Parylene N and Silverdag greatly enhanced the peak-to-valley ratio. Table II provides a summary of the data.

V. DISCUSSION

A. Teflon AF

The use of Teflon AF as the dielectric layer appears to introduce unwanted noise to the system. This effect was observed in more than one detector. The additional noise may be an artifact of the application method used. Spraying the Teflon AF onto the surface may yield a porous layer or uneven layer of Teflon AF on the surface after drying. A porous layer would not properly insulate the conductive Frisch collar from the CdZnTe surface. Further, it should be noted that the dielectric strength of Teflon AF is approximately an order of magnitude less than Parylene

N. If the thickness of the Teflon AF film was less than or approximately equal to $50 \mu\text{m}$ anywhere near the anode, then it is likely the added noise was due to dielectric breakdown.

The application of a conductive paint to the Teflon AF layer appeared to further degrade performance, even after the nickel-based paint was removed. Fig. 6 illustrates this fact as the noise seen in the low channels remained high even after the paint was removed.

B. Parylene N

Parylene N is a high resistivity, low dielectric permittivity version of parylene. The results seen in Detectors 2 through 4 indicate that vapor deposition of Parylene N is a good substitute for Teflon tape as the dielectric layer in a Frisch collar device. This is supported by the fact that noise was observed to

TABLE II

SUMMARY OF COLLECTED ENERGY RESOLUTION, PEAK-TO-VALLEY, AND PEAK EFFICIENCY DATA. %R IS THE NET PERCENT FULL WIDTH AT HALF MAXIMUM (FWHM) ENERGY RESOLUTION AT 662 KEV OF THE DETECTOR, P: V IS THE PEAK-TO-VALLEY RATIO AND E_f IS A MEASURE OF THE FULL ENERGY PEAK (FEP) EFFICIENCY. %R IS THE ENERGY RESOLUTION OF THE DETECTOR WITH THE PULSER FWHM QUADRATICALLY SUBTRACTED FROM THE TOTAL FWHM. E_f IS THE RATIO OF COUNTS UNDER THE FEP TO THOSE UNDER THE STANDARD TEFLON TAPE/COPPER SHIM FABRICATION METHOD FEP. UNCERTAINTY IN E_f EXISTS DUE TO UNCERTAINTY IN DETECTOR-SOURCE DISTANCE, d ($d = 15 \text{ mm} \pm 0.5 \text{ mm}$)

Detector	1			2			3			4		
New Dielectric	Teflon AF			Parylene N			Parylene N			Parylene N		
New Conductor	Ni-based Paint			Ni-based Paint			Ag-based Paint			Silverdag		
Fabrication Method	%R	P:V	E_f	%R	P:V	E_f	%R	P:V	E_f	%R	P:V	E_f
Teflon Tape/Copper Shim	2.2	12.1	1.00	2.5	4.7	1.00	1.6	5.4	1.00	1.7	13.5	1.00
New Dielectric/Copper Shim	2.8	6.4	0.67	3.2	4.0	1.06	2.2	4.4	0.65	2.1	11.1	1.00
New Dielectric/New Conductor	2.6	12.3	1.15	1.9	6.2	0.96	1.7	7.4	1.16	1.7	17.2	1.39

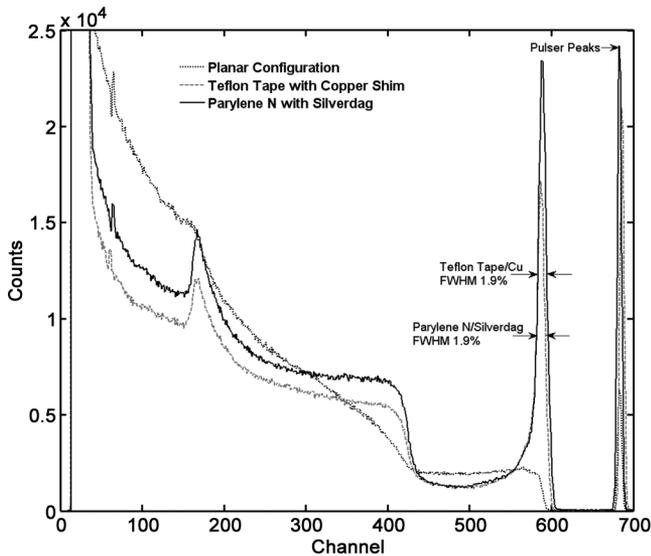


Fig. 12. Pulse height spectra of Detector 4 ($4.40 \times 4.75 \times 9.10 \text{ mm}^3$) comparing the standard Teflon tape and copper shim Frisch collar to the Frisch collar fabricated with Parylene N and Silverdag. Applied bias was 1000 V.

decrease or remain constant in Detectors 2 through 4 and energy resolution remained within one standard deviation or improved. Peak-to-valley ratios all improved significantly as well. Since the layer was at minimum $150 \pm 5 \mu\text{m}$ thick, electric field strength was at most 670 V per 100 μm , well below the dielectric breakdown strength of Parylene N.

It is apparent that using a copper shim as the Frisch collar with Parylene N acting as the dielectric degraded energy resolution. This was observed thrice as is shown in Figs. 7, 9 and 11). It is unknown why this phenomenon occurs. Nevertheless, energy resolution is restored or even improved when conductive paint or Silverdag is applied instead of the copper shim.

There was a noted difference in performance between the silver-based paint and the nickel-based paint. The nickel-based

paint appeared to improve energy resolution and decrease leakage noise as is visible in Fig. 8. The silver-based paint, on the other hand, did little to improve energy resolution. Similarly, the Silverdag did not improve energy resolution, but the peak-to-valley ratio increased dramatically from approximately 13.5:1 to 17.2:1 when compared against the standard Teflon tape/copper shim Frisch collar configuration.

VI. CONCLUSION

Considering the various aspects important to mass production, application of the dielectric layer is best performed through vapor deposition of Parylene N. Both nickel-based paint and silver-based paint appear to be acceptable substitutes for the conductive collar. However, the Silverdag provided the best improvement in device performance and was the simplest to apply given its fast drying rate.

A study of the long term effects of Parylene coatings is currently underway. Parylene is known to be a good moisture barrier, thus is likely to retard surface and contact degradation of the CdZnTe devices.

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