Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Nuclear Instruments and Methods in Physics Research A 515 (2003) 439–445
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

A first mass production of gas electron multipliers

P.S. Barbeau[a], J.I. Collar[a,*], J.D. Geissinger[b], J. Miyamoto[c], I. Shipsey[c], R. Yang[b]

[a] *Enrico Fermi Institute and Center for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA*
[b] *3M Co., Microinterconnect Systems Division, Austin, TX 78726, USA*
[c] *Department of Physics, Purdue University, W. Lafayette, IN 47907, USA*

Received 4 June 2003; accepted 13 June 2003

Abstract

We report on the manufacture of a first batch of approximately 2000 Gas Electron Multipliers (GEMs) using 3M's fully automated roll-to-roll flexible circuit production line. This process allows low-cost, reproducible fabrication of a high volume of GEMs of dimensions up to 30×30 cm^2. First tests indicate that the resulting GEMs have optimal properties as radiation detectors. Production techniques and preliminary measurements of GEM performance are described. This now demonstrated industrial capability should help further establish the prominence of micropattern gas detectors in accelerator-based and non-accelerator particle physics, imaging and photodetection.

PACS: 29.40.−n; 29.40.Cs; 29.40.Gx; 95.55.Vj; 85.60.Ha

Keywords: GEM; Radiation detectors; Gas-filled detectors

A number of new radiation detector designs, collectively referred to as Micropattern Gas Detectors (MPGDs) [1,2] have recently emerged in response to the extraordinary demands of next-generation High Energy Physics (HEP) experiments, namely the ability to respond to a high counting rate and integrated particle flux, superior radiation resistance and fine spatial resolution. Common to these designs is the presence of a large voltage drop (several hundred volts) across microstructures immersed in a suitable gas mixture. Electrons originating from ionization of the gas in a conversion volume drift to the region of the microstructures where the intense electric field allows gas amplification to occur. Due to the confined amplification regions, slow positive ions are removed immediately from the amplification volume, increasing rate capability by several orders of magnitude compared to wire-based gas detectors.

The attractive features of these detectors have lead to a growing number of applications in many fields. For instance, MICROMEGAS chambers [3] can be found nowadays in medical digital X-ray imaging equipment [4], where a high sensitivity in low-intensity radiation fields results in a diminished dose to the patient, while profiting from an enhanced image contrast. Similarly, photocathode-coated MPGDs promise to surpass photomultiplier tubes in light detection efficiency, reduced cost and speed [5,6]. Other emerging

*Corresponding author.
E-mail address: collar@uchicago.edu (J.I. Collar).

0168-9002/$ - see front matter
doi:10.1016/j.nima.2003.06.011

applications are industrial imaging [7] and X-ray astronomy [8]. Reviews of these can be found in Refs. [1,9].

Recently, it has been proposed to extend MPGD use to the field of non-accelerator particle physics [10,11], where uses would be numerous in view of their simplicity, the possibility to easily construct MPGDs out of radioclean materials and their very low-energy threshold. It is in the context of the development of a new type of neutrino detector [11] that we attempted to manufacture MPGDs in large numbers and with near-perfect reproducibility, using an industrial approach. This effort may nevertheless have repercussions in satisfying the large demand for MPGDs in accelerator-based physics. For this first attempt, we chose a popular design, the Gas Electron Multiplier (GEM) [12] given its particular simplicity of design. A GEM consists of a ~ 50 μm-thick polyimide (Kapton^{TM}) film copper clad on both sides, perforated with a regular matrix of small holes (diameter few tens of μm) produced by photolithography. When a voltage difference is applied between the two sides of the GEM, a large electric field is produced in the holes. Electrons that enter the holes undergo gas amplification. A remarkable advantage of GEMs is the possibility of building multi-stage amplification layers [13], where electrons are transferred from one GEM to the next, undergoing successive avalanches and yielding very large charge gains. The resulting high-efficiency for single electron detection looks particularly attractive to us, when considering the small energy depositions expected from low-energy neutrino recoils [11].

We report here on preliminary tests and observations made on a first batch of ~ 2000 GEMS (Fig. 1) produced using 3M's high volume, wide web, roll-to-roll, adhesiveless flexible circuit (FLEX) making process (Fig. 2). At the time of this writing every indication points at their having a satisfactory performance as radiation detectors. Our preliminary results are encouraging but testing is in an early stage. For example, we have not yet studied the resistance to radiation (aging) of the GEM. We, however, feel that the widespread demand for GEMs by numerous research groups justifies the early release of our findings.

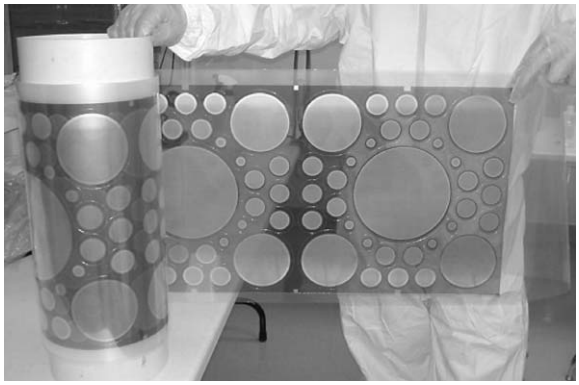

Fig. 1. Single continuous roll containing a production of ~ 1000 subtractive GEM elements in different sizes. Barely visible in the figure are perforations made around each GEM to facilitate detachment. The maximum GEM area permitted at present in 3M's production line is $30 \times 30\ \mathrm{cm}^2$, already comparable to the largest MPGDs produced for high-energy physics experiments.

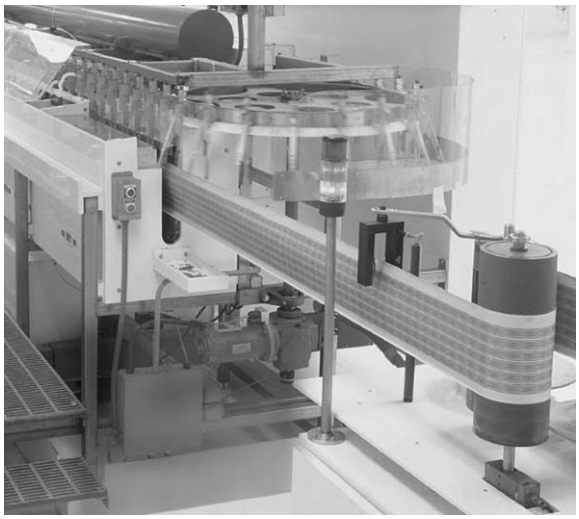

Fig. 2. 3M's roll-to-roll flexible circuit manufacture in clean room conditions.

Flexible circuits are utilized in a variety of applications such as inkjet printer cartridges, hard disk drives, liquid crystal display modules, and IC packages among others [14]. These applications have a variety of needs that are met with various FLEX circuit constructions. These can be grouped into two categories: 3-layer and adhesiveless FLEX circuits [15]. A 3-layer FLEX is appropriately

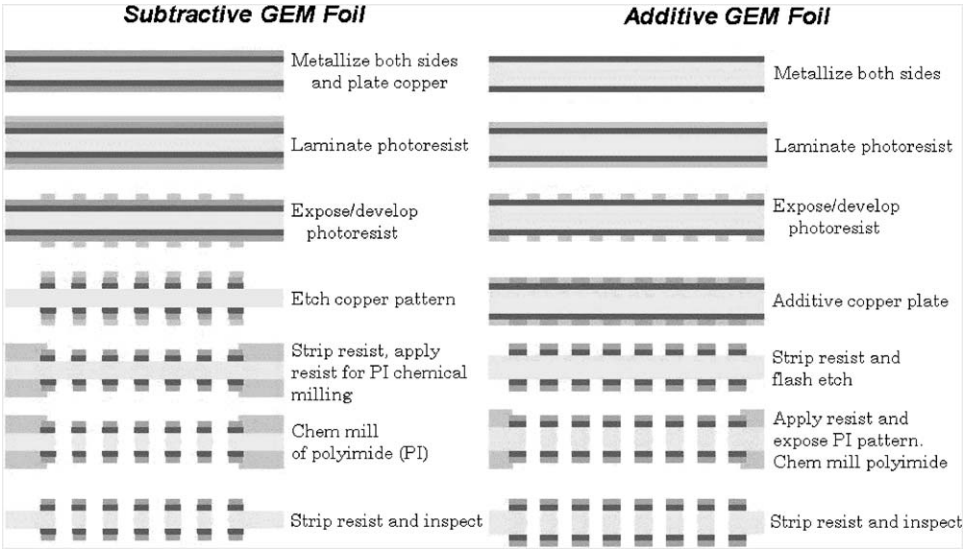

Fig. 3. Subtractive and additive process flows used in the manufacture of 3M's GEM foils.

named since it is constructed from a copper foil, a polymeric film, and an adhesive to bond foil to film. In many applications such as hard disk drives and GEMs, the presence of the adhesive would create outgassing and ionic problems. An adhesiveless FLEX circuit (also referred to as a 2-layer FLEX) requires alternative means for securely bonding the copper to the polymer. The two primary methods for fabricating an adhesiveless FLEX circuit are (a) direct metallization of the polymeric film and (b) casting of liquid polyimide onto the Cu foil. After the substrate has been created, the copper and polyimide materials must be patterned to form the desired geometry for the application. The copper pattern can be formed by using either an additive or subtractive circuitization process. The process flows for each are illustrated in Fig. 3.

The additive process consists of applying a photo resist imaged with the desired copper pattern to a 50 μm-thick polyimide film, directly metallized on both sides. The copper is then electroplated to the appropriate thickness onto the exposed flash layer. This plating technique can allow for a wide range of copper thicknesses ranging from 4 to 36 μm. As shown in Fig. 4, this additive circuitization process can achieve very fine copper features [16], down to 20 μm trace and

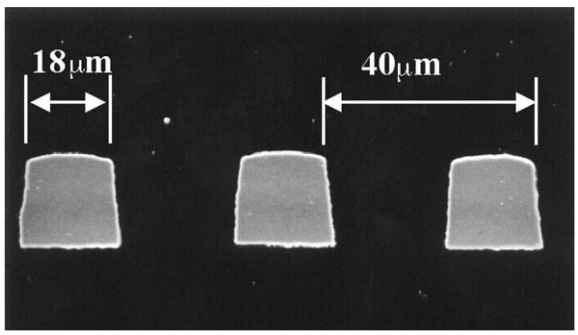

Fig. 4. 40 μm pitch circuitization on 1-metal layer FLEX (see text).

20 μm space on 1-metal layer FLEX circuits (30 μm traces and 30 μm spaces on 2-metal layer FLEX circuits). As can be seen in the trace cross-section in the figure, the sidewalls on the additive copper are nearly vertical.

GEM foils were also manufactured using the subtractive process flow outlined in Fig. 3. The subtractive structure is believed to be similar to the construction described by Bouclier et al. [17]. The side walls of the copper openings have a somewhat shallower slope than in the additive process. GEMs produced with these two different circuitization processes showed some performance differences described below.

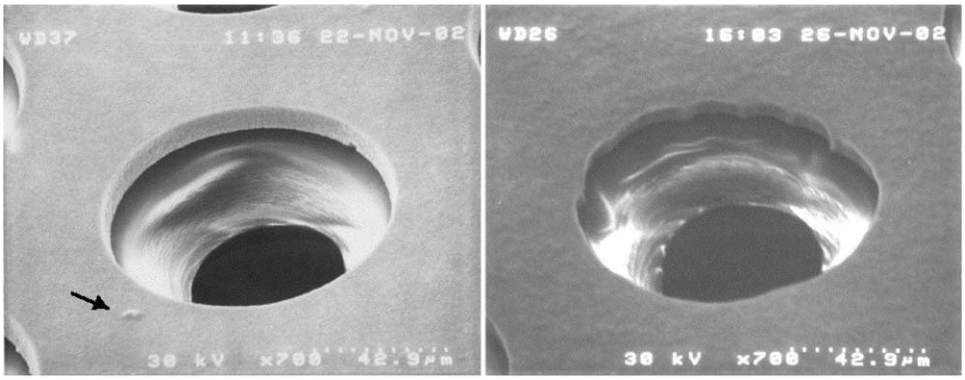

Fig. 5. Scanning electron microscope images of 3M subtractive (left) and additive GEMs (right). A small Cu microcrystal (height <1 μm) is indicated by an arrow on the subtractive surface. No sparking or other spurious effects have been observed from these. Additive GEMs display smoother surfaces but copper opening irregularities can be identified on large areas of the panels. An extreme case is depicted here (see text).

One lot from each fabrication method has been produced so far, each containing $\sim$30 identical panels of 33 GEM elements (Fig. 1). Production of a much larger number of panels per lot, up to a few hundred, is possible. In both cases the chosen design was the so-called "standard GEM" [18], i.e., 80 μm holes in an hexagonal pattern with 140 μm pitch and a biconical transversal hole cross-section. In other words, the innermost part of the holes exhibits a reduced opening of $\sim$55 μm, a characteristic also found in most GEMs built elsewhere. The use of Dupont E-film Kapton^{TM} as the substrate does not allow to reduce this opening any further. In the present lots, the copper thickness was fixed at 12 μm to insure the success of these first trials. In successive attempts this will be further reduced, a feature of interest for tracking devices where multiple scattering in the detector must be minimized.

The surface quality of both lots has been studied via SEM (Fig. 5) and AFM (Fig. 6). Slight copper opening irregularities are observable mostly on one side of these first additive GEMs. This may lead to gain inhomogeneities across the GEM surface: therefore, we have concentrated at first on the characterization of the subtractive lot. The additive fabrication process has proven to be challenging: small polyimide ribs stemming from the interior of the holes were initially observed to envelope the edges of copper openings. Additional treatment of the lot removed these but resulted in a slightly diminished copper to polyimide attachment[1] and the previously mentioned irregularities. The smoother copper surface quality obtained with this method (Fig. 6) is nevertheless a redeeming quality that justifies further exploration: it may be of importance in applications where total inhibition of field effect electron emission is sought, as is the case in Ref. [11] and other efforts concerned with single-electron detection [6]. The subtractive surfaces exhibit apparently innocuous copper microcrystallite growths (Fig. 5): while we have not observed any sparking nor other unexpected behavior from their presence, the contributing factors that lead to their formation have been determined and future foils will be much more uniform/smooth in appearance.

Figs. 7–10 incorporate the extent of our preliminary characterization of subtractive 3M GEMs. Fig. 7 shows typical leakage currents measured in a number of randomly selected GEMs. They consistently display values comparable to previously produced GEMs. However, we have not yet observed any need to "cure" or

[1] It must be noted that the method used to test copper to polyimide attachment is probably too stringent, consisting of firmly attaching adhesive tape to the GEM surface and swiftly peeling it off. Only some additive 3M GEMs are seen *not* to pass the test. With any luck a GEM should not have to withstand such abuse during normal operation.

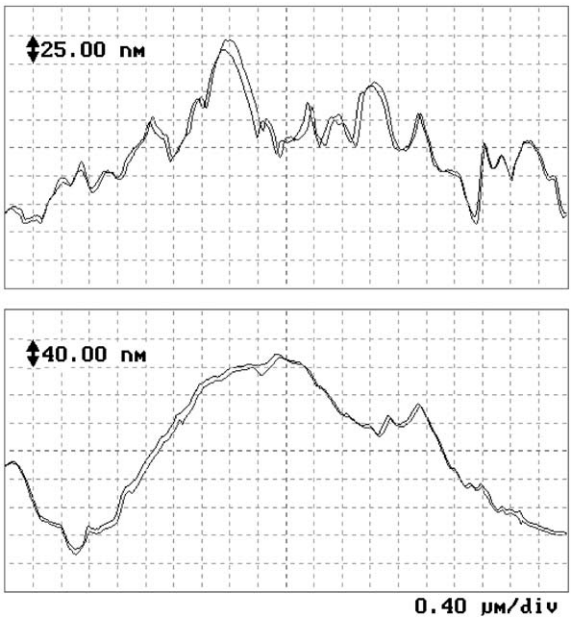

Fig. 6. Typical surface roughness in 3M's subtractive (top) and additive GEMs (bottom): the figures show tip traces and retraces from contact-mode atomic force microscopy, scanning along a straight line. The smoother additive relief may be preferable in applications where field effect electron emission must be kept down to an absolute minimum. Note the difference in vertical scale.

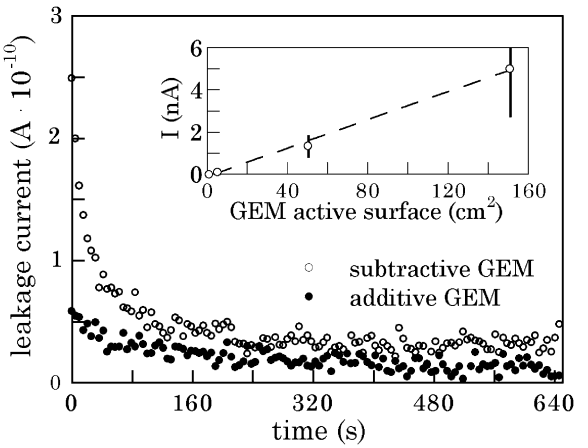

Fig. 7. Leakage current in air (~40% humidity) across 5 cm^2 additive and subtractive 3M GEMs. A 600 V bias was applied using tin clamps on their outermost ~0.5 cm (this annular region is devoid of holes to facilitate soldering). The measurements were performed with a Keithley 6485 picoammeter. The GEMs were enclosed in a special double shielding to attenuate RFI/EMI interference [19]. Inset: Dependence of the leakage current (asymptotic value after several hours) on subtractive GEM active surface area. A total of approximately 20 randomly selected GEMs have been characterized, all displaying similar low values. The figure shows averages and their dispersion.

"burn" 3M GEMs against shorts able to suddenly raise this current into the μA range, as is sometimes necessary with other GEMs. The good behavior of these leakage currents over periods of several hours probably comes from the homogeneous surface treatment that the fully automated roll-to-roll process guarantees, together with the use of high-purity polyimide, free of any fillers. Each part of each GEM foil receives an identical treatment in every fabrication step, something hard to achieve in manual production runs, especially over large surface areas. For the same reasons we expect a good gain uniformity over large GEM surfaces. An optimal energy resolution in the presence of an uncollimated ^{55}Fe source, as evidenced in Fig. 8, points in this direction. As a matter of fact, first tests of gain uniformity (Fig. 9) yield values already comparable to other MPGDs [20]. Finally, Fig. 10 displays the gas gain measured using the GEMs as an isolated detector, i.e., without a charge collection backpanel anode. We observe no deviation from the expected behavior, nor any anomaly in the onset of discharges (at about $V_{GEM} = 450$ V in Ar + 10% DME and 600 V in Ar:CO_2).

While the R&D on these GEMs has barely started, all observations are presently very encouraging. First trials with a liquid crystal polymer (LCP) substrate show near-cylindrical hole walls, which can be of interest in applications where excessive dielectric charge-up via ion deposition is a concern (this can lead to a diminished gain uniformity across the surface). Other advantages of LCP compared to Kapton™ [21] are a much smaller maximum water absorption (0.1% vs. 2%, which may result in lower outgas, of relevance in HEP applications where extreme gas purity is required), better dielectric properties and a higher chemical and heat resistance. The last may result in GEMs more compatible with soldering and operation in commonly used etching detector gases such as CF_4, and possibly more resistant to

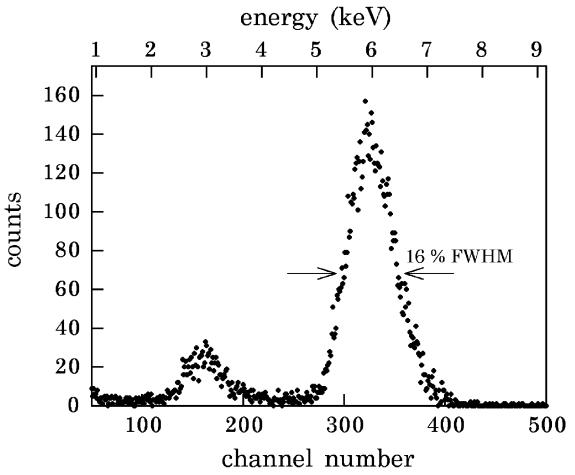

Fig. 8. Characteristic spectrum from an uncollimated ^{55}Fe source and a single subtractive 3M GEM in Ar + 5% CH_4 (active area 5 cm^2, $V_{drift} = 500$ V, $V_{GEM} = 480$ V). The signals were read off the lower GEM electrode with a grounded PCB immediately beneath it to aid charge collection, passed on to an ORTEC 142AH low-noise preamplifier and recorded using a XIA POLARIS digital spectrometer. Good energy resolution in the presence of an uncollimated source can be an indicator of adequate gain uniformity across the surface. ^{55}Fe resolutions down to ~14% have been obtained from this lot in much less than optimal conditions (stagnant gas, uncollimated source, ~10 cm drift length in an inhomogeneous drift field).

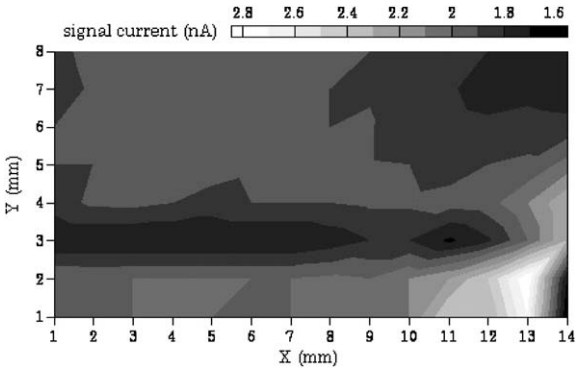

Fig. 9. Gain uniformity in Ar:DME (9:1) for a subtractive 3M GEM irradiated with a strong 5.4 keV X-ray source focused on a 1 mm^2 spot. The current generated was measured with a picoammeter directly from the bottom GEM electrode ($V_{drift} = 600$ V, $V_{GEM} = 400$ V). The measured dispersion (standard deviation of 112 measurements) is 9%.

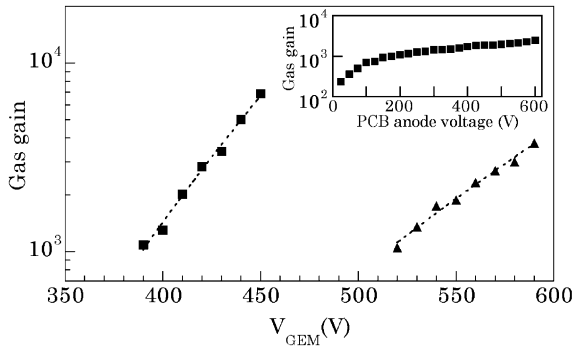

Fig. 10. Gain from an 8-cm-diameter subtractive 3M GEM in Ar:DME (9:1, squares) and Ar:CO_2 (7:3, triangles) as a function of voltage across the element, in the presence of an uncollimated ^{55}Fe source. Charge amplification was obtained with an ORTEC 142PC preamplifier collecting from the GEM lower electrode. The drift voltage was −500 V. Inset: Gain in Ar:DME (9:1) using the more conventional approach of collecting from a single-channel PCB readout placed 1 mm below the GEM ($V_{GEM\ UPPER} = -400$ V, $V_{GEM\ LOWER} = 0$ V), as a function of V_{PCB}.

sparking. We expect to be able to report on LCP-GEMs soon.

Hopefully the methods presented here will enable the production of large-area MPGD's. These will be required in large next-generation time-projection chambers, the leading candidate for the tracking system at the next linear collider [22] and also a possible contender in future underground physics experiments [10]. Proposals for hadron-blind GEM-based detectors in heavy-ion physics programs [23] and for large-area, high-rate neutron detectors [24] may similarly benefit.

Tested GEM samples can be obtained from collar@uchicago.edu. JIC and PB would like to thank Q. Guo for his assistance in performing SEM and AFM measurements and T. Witten for helpful discussions. JM and IPJS thank Kirk Arndt and Tom Smith of the Department for Physics at Purdue University for technical support.

References

[1] F. Sauli, A. Sharma, Ann. Rev. Nucl. Part. Sci. 49 (1999) 341;
F. Sauli, Nucl. Instr. and Meth. A 461 (2001) 47.
[2] A. Oed, Nucl. Instr. and Meth. A 471 (2001) 109;
L. Shekhtman, Nucl. Instr. and Meth. A 494 (2002) 128.

[3] Y. Giomataris, Ph. Rebourgeard, J.P. Robert, G. Charpak, Nucl. Instr. and Meth. A 376 (1996) 29.
[4] http://www.biospace.fr/en/xray.php.
[5] J. Derré, Y. Giomataris, Ph. Rebourgeard, H. Zaccone, J.P. Perroud, G. Charpak, Nucl. Instr. and Meth. A 449 (2000) 314.
[6] R. Chechik, M. Balcerzyk, A. Breskin, A. Buzulutskov, G.P. Guedes, D. Mormann, B.K. Singh, Nucl. Instr. and Meth. A 502 (1) (2003) 195.
[7] F.A.F. Fraga, S.T.G. Fetal, L.M.S. Margato, I. Ivaniouchenkov, R.F. Marques, A.J.P.L. Policarpo, 1999 IEEE Nuclear Science Symposium Conf. Rec., Piscataway, NJ, USA. IEEE Part 2 (1999) 829;
M. Li, M.S. Dixit, P. Johns, Nucl. Instr. and Meth. A 471 (2001) 215.
[8] E. Costa, P. Soffitta, R. Bellazzini, A. Brez, N. Lumb, G. Spandre, Nature 411 (2001) 662.
[9] A. Sharma, CERN Courier 41 (2001) (http://www.cern-courier.com/).
[10] J.I. Collar, Y. Giomataris, Nucl. Instr. and Meth. A 471 (2001) 254 (hep-ex/0009063).
[11] P. Barbeau, J.I. Collar, J. Miyamoto, I. Shipsey, Proceedings of the 2002 IEEE Nuclear Science Symposium and Medical Imaging Conference, Norfolk, VA, November 10–16, 2002 IEEE Trans. Nucl. Sci. (hep-ex/0212034), in press.
[12] F. Sauli, Nucl. Instr. and Meth. A 386 (1997) 531;
F. Sauli, US Patent #6,011,265, granted January 4, 2000.
[13] A. Buzulutskov, A. Breskin, R. Chechik, G. Garty, F. Sauli, L. Shekhtman, Nucl. Instr. and Meth. A 443 (2000) 164;
L. Guirl, S. Kane, J. May, J. Miyamoto, I. Shipsey, Nucl. Instr. and Meth. A 478 (2002) 263.
[14] E. Jan Vardaman, Circuit World 26, September 2000, 15.
[15] T.R. Bergstresser, J.S. Sallo, Proceedings of the IPC Chip Scale and BGA National Symposium Proceedings: Pursuit of the Perfect Package, Santa Clara, CA, USA, May 6–7, Vol. 1 1999, p. 143.
[16] B. Chou, S. Beilin, H. Jiang, D. Kudzuma, M. Lee, M. McCormack, T. Massingill, M. Peters, J. Roman, Y. Takahashi, V. Wang, Proceedings of the 1999 International Conference on High Density Packaging and MCMs, April 6–9, Denver, CO, 1999, p. 270;
J. Geissinger, F. Keller, S. Trevino, T. Kamei, Proceedings of the 27th Annual IEEE/CPMT/SEMI International Electronics Manufacturing Technology Symposium, San Jose, CA, USA, 17–18 July 2002, p. 41.
[17] R. Bouclier, M. Capeans, W. Dominik, M. Hoch, J.C. Labbe, G. Million, L. Ropelewski, F. Sauli, A. Sharma, Proceedings of IEEE Trans. Nucl. Sci. (USA), Vol. 3, Anaheim, CA, USA, 3–9 Nov. 1996, 44, p. 646.
[18] J. Benlloch, A. Bressan, C. Buttner, M. Capeans, M. Gruwe, M. Hoch, J.C. Labbe, A. Placci, L. Ropelewski, F. Sauli, A. Sharma, R. Veenhof, IEEE Tran. Nucl. Sci. NS-45 (1998) 234.
[19] Low Level Measurements, Keithley Publication No. 1559, 5th Edition.
[20] S. Beirle, U. Werthenbach, G. Zech, T. Zeuner, Nucl. Instr. and Meth. A 423 (1999) 297;
S. Kane, J. May, J. Miyamoto, I. Shipsey, I. Giomataris, 2001 IEEE Nuclear Science Symposium Conference Rec., Piscataway, NJ, USA, IEEE Part 1 (2002) 265.
[21] T.F. Hayden, Proceedings of the 2002 International Conference on Advanced Packaging and Systems (ICAPS), Reno, NV, March 10–13, 2002;
R. Yang, Advanced Packaging, March 2002 (http://ap.pennnet.com/).
[22] M. Schumacher, Proceedings of Physics and Experiments with Future Linear e^+e^- Colliders, LCWS 2000, Batavia, IL, USA, 24–28 October 2000, AIP Conf. Procs. 578 (2001) 821.
[23] C. Aidala, B. Azmoun, Z. Fraenkel, T. Hemmick, B. Khachaturov, A. Kozlov, A. Milov, I. Ravinovich, I. Tserruya, S. Stoll, C. Woody, S. Zhou, Nucl. Instr. and Meth. A 502 (1) (2003) 200.
[24] M. Klein, H. Abele, D. Fiolka, C.J. Schmidt, Proceedings of Art and Symmetry in Experimental Physics, Berkeley, CA, USA, 20–21 May 2001, Am. Inst. Phy. Conf. Procs., 596 (2001) 193.