Hard X-ray spectroscopy using a small format TiBr array

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Hard X-ray spectroscopy using a small format TlBr array

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We report X-ray measurements on a prototype $3 \times 3$ TlBr pixel array, produced to assess the technological feasibility of making a Fano limited imager, which can operate near room temperature. The device was fabricated on mono-crystalline material of size $2.7 \times 2.7 \times 1.0 \text{ mm}^3$. It has a pixel size of $350 \times 350 \text{ microns}^2$ and pitch of 450 $\mu\text{m}$. Measurements were carried out on all pixels over the energy range 5.9 keV to 662 keV using radioactive sources. The leakage currents were found to be low enough to allow room temperature operation, with typical energy resolutions of $\sim 20 \text{ keV FWHM}$ at 59.95 keV under full-area illumination. At a reduced detector temperature of $\sim 30^\circ\text{C}$, these fell to $\sim 4 \text{ keV FWHM}$. Although the spectral performance of the present array is currently impaired by material limitations, its spectral acuity was found to be greatly enhanced by the small pixel effect.

Additional photon metrology was carried out at the Hamburger Synchrotronstrahlungslabor (HASYLAB) radiation facility. Under monochromatic pencil beam illumination, the measured energy resolutions at 20 keV were $\sim 3 \text{ keV FWHM}$ at $\sim 30^\circ\text{C}$. The spatial uniformity of the array was measured using a $50 \times 50 \text{ $\mu\text{m}^2$}$, 20 keV mono-energetic X-ray beam, raster-scanned over the entire active area. The response, in terms of count rate, gain and energy resolution was found to be uniform at the few percent level, consistent with statistics. It was observed during these measurements, that the X-ray response of the pixels was unstable, showing time dependent gain shifts indicative of polarization effects. The magnitude of the effect was proportional to the total energy deposition per unit time.

Lastly, the use of TlBr arrays in nuclear medicine applications is discussed with particular emphasis on radio-guided surgical probes. Recommendations for an optimized design are given.

Keywords: Compound semiconductors, TlBr, X-rays. PACS: 07.85Nc, 29.40Wk, 81.05Dz.

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1. Introduction

For an increasing range of applications, compound semiconductors have attracted considerable interest as viable alternatives to silicon and germanium. In particular, for those applications where room temperature operation, high stopping power or the ability to operate in high radiation environments, is desirable. Those applications, in fact, for which the elemental semiconductors are clearly unsuitable because of their narrow band gaps and relatively low densities. Compound semiconductors, on the other hand, are available in a range of band-gaps and stopping powers, leading to the possibility that materials can be engineered for specific applications and wavelengths. For the soft X-ray to the hard X-ray region, GaAs is particularly suitable and has already demonstrated near Fano energy resolution [1]. In the hard X-ray band, CdTe and CdZnTe are routinely used, although both materials suffer from poor hole transport properties which limits the maximum thickness and therefore high energy response of detectors. For higher energies and specifically γ-ray applications, thallium bromide has emerged as a particularly interesting material in view of its wide band-gap (2.5 times that of Si) and its large density of 7.5 g cm\(^{-3}\) (3.2 times that of Si). In fact, with the exception of some lead compounds, it has a larger stopping power for hard X- and γ-rays than any other semiconductor \((Z_{Te}=81, Z_{Br}=35)\).

TlBr was originally demonstrated as a radiation detector material by Hofstadter in 1949 [2] - albeit with limited success due to purity and fabrication problems. Surprisingly, compared to other compound semiconductors, relatively little work has been carried out since this time [3-9]. Recently, Owens et al. [10] have produced a series of monolithic detectors of area \ (~8 mm\(^2\) and thickness \ (~800 μm with demonstrated room temperature performances of 1.8 keV FWHM at 5.9 keV and 3.3 keV FWHM at 59.54 keV. With only modest cooling (-30°C), these fall to 800 eV and 2.6 keV FWHM, respectively. The focus of this research has been to address the material, electronic and technological issues that need to be solved in order to develop practical, hard X- and γ-ray detectors. Building on this work, we have now produced the first small-format array to explore array design and operation. The pixel size was chosen primarily by the ease with which they could be instrumented and the ability to carry out detailed and spatially resolved metrology at the pixel level. Two application areas are being considered; a) the production of large format spectroscopic imagers for gamma-ray astrophysics, and b) intermediate/small format hard X-ray arrays suitable for synchrotron beam studies and nuclear medicine applications.

2. Detector fabrication

TlBr was produced by synthesis from nitric-acid solution and purified by vacuum distillation. A monocrystalline boule was grown from the base material by the
Bridgeman-Stockbarger method. The boule was then sawn into several 1 and 2 mm thick wafers using a wire saw and lapped with diamond paste, followed by mechanical

Fig. 1. Schematic of the array showing pixel layout, dimensions and numbering convention.
and chemical polishing to an optically smooth and transparent finish. A number of detector platelets were diced from the wafers and a single crystal of dimensions \(2.7 \times 2.7 \times 1.0 \text{ mm}^3\) selected, based on its specific resistance and optical purity. After surface processing, gold contacts were evaporated onto the crystal through a shadow mask, forming a planar surface on the cathode and a \(3 \times 3\) pixel structure on the anode, surrounded by a guard ring. A schematic of the device is shown in fig. 1. The pixel dimensions were \(350 \times 350 \text{ \mu m}^2\), with an inter-pixel gap of 100 \(\mu \text{m}\). The array was glued to a dielectric substrate, which in turn, was mounted on a three-stage Peltier cooler, capable of cooling the device to \(-40^\circ\text{C}\). The device is illuminated through the cathode. Each pixel was instrumented with its own resistive feedback preamplifier. The numbering convention for the pixels is illustrated in fig 1. Contacting to the preamplifier input stages (which were also integrated on the substrate) was achieved via wire-bonding. The rest of the analog chain is mounted externally on an outer vacuum vessel. This vessel has a thin Be window to facilitate the efficient transmission of soft photons to the detector. In fig. 2 we show the completed detector assembly with its support electronics.

![Figure 2](image_url)

*Fig. 2. Photograph of the completed detector plus support electronics.*

### 2.1 Electrical characteristics

From the I-V characteristics, the typical leakage currents at a bias of 50 V were \(-24\) pA at room temperature and \(-2\) pA at \(-10^\circ\text{C}\). The pixel resistivities were found to be
in the range (6 - 10) \times 10^{10} \text{ } \Omega \text{ cm and the inter-pixel resistance } \sim 500 \text{ } \text{G}\Omega \text{ with } 50\text{V differential between pixels. This is much higher than for CdZnTe, which means that Frisch grid methods could be effectively used to measure only the electron signal.}

Initial tests showed that biasing the detector to preferentially collect holes from the illuminated electrode gave significantly better spectral resolution than collecting electrons. This reflects the poor \( \mu t \) product for holes in TlBr, which is more than a factor of 20 lower than that for electrons [10]. By biasing this electrode to collect holes, charge collection is improved as the holes only have to travel a short distance to be collected and are less likely to be trapped.

The preamplifier outputs are fed to spectroscopy amplifiers and then to a linear fan-in whose output is digitized by an Amptek MCA8000 12-bit ADC and stored on a PC. Real time analysis is carried out by pipelined software based on IDL.

![Graph](image)

**Fig. 3.** The variation of peak channel (open circles) and energy resolution (solid circles) of pixel 3-3 as a function of amplifier shaping time at 59.54 keV, incident energy. The solid line through the resolution data points shows the expected variation. For completeness, the individual noise components are also shown.

### 3. Laboratory measurements

The initial characterization was carried out using \(^{55}\text{Fe}, ^{57}\text{Co}, ^{137}\text{Cs}\) and \(^{241}\text{Am}\) radioactive sources. Fig. 3 shows the measured FWHM energy resolution and peak
channel position of pixel 3-3, as a function of amplifier shaping time constant. The incident X-ray energy was 59.54 keV, the detector temperature, \(-20^\circ C\) and the applied bias, \(-300\text{V}\). At short shaping times, the noise curve displays the characteristic \(t^{0.5}\) fall-off expected from series noise (i.e., Johnson noise produced in the input FET and biasing components). At longer shaping times, the response follows the expected \(t^{0.5}\)

**Fig. 4.** The variation of fwhm energy resolution of pixel 3-3 (solid circles) and the peak channel position (open circles) at 59.5 keV with detector temperature.

dependence of parallel noise. \(1/f\) noise, arising from the input FET and dielectric loses in the front-end components, is negligible. The solid line through the resolution data points is the expected noise function. Based on this curve, a shaping time of 6 \(\mu\text{s}\) was used in subsequent measurements. For completeness, we show the individual noise components separately. Lastly, we note that for shaping times longer than \(\sim 3\ \mu\text{s}\), the variation in peak channel position is \(< 5\%\), indicating that ballistic deficiency effects will be small.

In fig. 4, we show the measured temperature dependence of both the peak channel position (i.e., gain) and the FWHM energy resolution. Surprisingly, the energy resolution shows little variation below \(0^\circ\text{C}\). In fact, \(\Delta E\) decreases by \(\sim 0.5\%\) per °C, whereas the gain decreases by about \(2\%\) per °C.

The energy resolution function of the center pixel (2-2) was determined from pulse height data and is shown in fig. 5. The fwhm resolutions, under full-area illumination,
range from 1.8 keV at 5.9 keV to 29 keV eV at 662 keV. The measured resolutions, \( \Delta E \), were found to be well-fit by a semi-empirical function of the form,

\[
\Delta E = 2.355 \sqrt{FeE + (\Delta e / 2.355)^2 + a_1 E^2},
\]

where the first term in the square root represents the component due to Fano noise. Here \( F \) is the Fano factor, \( E \) is the incident energy and \( e \) is the electron-hole pair creation energy (6.5 eV [11]). The second term is the component due to the electronic noise of the system; where \( \Delta e \) is the FWHM electronic noise width as measured with a precision pulser. This was 1.7 keV FWHM. The third term is due to incomplete charge collection or trapping noise, where \( a_1 \) and \( a_2 \) are semi-empirical constants determined by best-fitting. Allowing \( F \) to be a fitted parameter resulted in unphysical values. Therefore, in analogy with other semiconductors, its value was fixed at 0.12. The solid line in fig. 5 shows the best-fit resolution function and the broken lines its individual components. From the figure, we note that electronic noise dominates the response below 60 keV, while trapping noise dominates above. In no energy region is Fano noise significant.
In fig. 6, we show the arrays response to $^{241}$Am, from which it can be seen that the spectroscopic quality of pixels varies considerably - even though the individual I-V and temperature characteristics are similar. Part of the problem stems from the inability to apply a high enough common bias to the cathode and still be able to operate all pixels within the operational envelope of the preamplifiers, i.e., without saturating some of them. The spectra shown in fig. 6 were obtained with a maximum potential of $-300\,\text{V}$. For the principal nuclear line at $59.54\,\text{keV}$, there is a $23\%$ spread in gains and the measured FWHM energy resolutions range from $2.9\,\text{keV}$ to $6.3\,\text{keV}$. The corresponding pulser resolutions range from $1\,\text{keV}$ to $1.9\,\text{keV}$. At higher biases some of the pixels began to breakdown, while at lower biases the resolutions degrade rapidly. For example, at $-200\,\text{V}$ common bias, the average resolution was $\sim 20\,\text{keV}$ FWHM at $59.54\,\text{keV}$. Optimizing the operating conditions of some individual pixels at the expense of others, resulted in a marked improvement. For example, increasing the bias from $300\,\text{V}$ to $400\,\text{V}$, resulted in a reduction in energy resolution of pixels 2-2 and 2-3 from $\sim 4\,\text{keV}$ to $\sim 2\,\text{keV}$ FWHM at $59.54\,\text{keV}$ and a clear improvement in overall spectral quality. This is illustrated in fig. 7 from which we can see that even the neptunium Lα, Lβ and Lγ lines are clearly resolved. However, at this bias, the leakage currents of 3 other pixels were so large that they saturated the preamplifiers. Because

![Fig. 6. Collage of $^{241}$Am spectra measured at $T=-20^\circ\text{C}$; $V=-300\,\text{V}$ and $t=6\mu\text{s}$ from all pixels of the array. The measured FWHM energy resolutions at $59.54\,\text{keV}$ range from $2.9\,\text{keV}$ (3-3) to $6.3\,\text{keV}$ (3-2).](image-url)
TIBr is so soft, we attribute the wide variation in X-ray response between pixels to material damage introduced during the fabrication process.

Fig. 7. Optimized $^{241}$Am spectra obtained from pixel 2-2 (left) and pixel 2-3 (right). The operating parameters were, $T = -30^\circ C$, $V = -400V$ and $t = 6 \mu s$. The right hand peaks are the pulser. The measured energy resolutions are $\sim 2.2$ keV at 59.54 keV, with an electronic noise component of 1 keV FWHM. These should be compared to the degraded spectra shown in fig. 6.

3.1 Small pixel effect

Recently, Barrett, Eskin and Barber [12] have shown that the deleterious effects of hole trapping are greatly reduced if the pixel dimension, $t$, is made small relative to the detector thickness, $L$. This is a direct consequence of the electrostatics of the signal induction process and is generally referred to as the small-pixel, or near field, effect. The net result is clearly demonstrated in fig. 8, in which we have over-plotted one of the $^{241}$Am spectra shown in fig. 7 ($t/L = 0.35$; broken line), with a spectrum obtained with a $2.7 \times 2.7 \times 0.8 \text{ mm}^3$ planar detector ($t/L = 3.4$; solid line) fabricated from the same wafer material and using the same contacting technology. The energy scale of the planar detector has been renormalized to be the same as the pixel detector at the Np L$\alpha$ line at 13.64 keV (note we have also normalized its peak amplitude to be the same also). At this energy, it is assumed that X-rays interact so close to the cathode that both devices are 100% efficient. From the figure, it is clear that the gains of the planar and pixel detectors and therefore their charge collection efficiencies (CCEs) are different, since the apparent measured energy-losses become increasingly divergent at higher energies. In fact, the CCE of the pixel detector is 22 % larger than the planar device and this is entirely due to near-field effects. Additionally, the tailing due to hole trapping is greatly reduced and the amplitude of the nuclear line increased. The dramatic reduction in line tailing is illustrated by the inset of fig. 8, in which we have overlayed the planar and pixel detector photopeaks at 59.54 keV. In this case, we have renormalized the 59.54 keV nuclear line peak of the planar detector, both in energy-loss and amplitude. Neglecting the fact that their original absolute amplitudes are different, the electron components are clearly similar. This is most easily seen, or
understood, as the right hand side of the peaks - the left hand side being skewed by the tailed hole component. However, for the pixel detector, the hole component is greatly suppressed, much improving spectral acuity. In fact, the peak to tail ratio has increased by a factor of 10. Finally, we should point out that the bias applied to the planar detector was considerably larger than that applied to the pixel detectors (560 V as opposed to 400 V). This accounts for its apparently much better spectral resolution at low energies.

![Graph showing normalized counts vs energy (keV) for pixel and planar detectors.](image)

**Fig. 8.** Demonstration of the small pixel effect in TiBr, in which its spectral properties are greatly influenced by pixel geometry and specifically the ratio of the pixel dimension, $t$, to its thickness $L$. Here we show two $^{240}$Am spectra - one recorded by pixel 2-2 ($t/L = 0.35$, broken line) and the other by a $2.7 \times 2.7 \times 0.8 \text{ mm}^3$ planar detector ($t/L = 3.4$, solid line). The energy scale of the planar device has been normalized to that of the pixel detector at the Np Lα line at 13.54 keV. Note, at higher energies the lines no longer coincide in energy, indicating that the charge collection efficiency of the planar device is significantly lower than that of the pixel detector. In the inset, we have changed the energy scale of the 59.54 keV nuclear line peak from the planar detector (both in energy-loss and amplitude) to overlay the photopeak of the pixel detector to demonstrate hole suppression due to the small pixel, or near field effect.

4. **Synchrotron radiation measurements**

X-ray measurements were also carried out at the X-1 beamline [13] at the HASYLAB synchrotron radiation facility. This beamline utilizes a channel-cut double...
crystal monochromator to produce highly monochromatic X-ray beams across the energy range 12 keV to 100 keV. To cover such a large energy range, a Si[511] reflection is used, yielding an intrinsic energy resolution of \( \sim 1 \) eV at 10 keV rising to 20 eV at 100 keV. The array was mounted on an X-Y table capable of positioning the sensitive elements to an absolute precision of \( \pm 1 \) \( \mu \)m in each axis. The beam was collimated by a set of slits placed immediately in front of the array to a size of 50 \( \times \) 50 \( \mu \)m\(^2\). The array was operated at a temperature of \(-30^\circ\)C and a common pixel bias of \(-300\)V. Pulse height measurements taken with pixel 3-3, gave a FWHM energy resolution of 2.5 keV at 20 keV. This is consistent with that expected from fig. 5, when one considers that the data shown in fig. 5 pertains to full-area illumination.

While all pixels behaved well at energies below \( \sim 20 \) keV, above this energy they became unstable displaying gross gain shifts and effects akin to the polarization phenomena normally observed in, say, HgI\(_2\) detectors. The magnitude of this effect shows proportionality to the total energy deposition per unit time. For example, at 20 keV and a count rate of \( \sim 200 \) cps\(^{-1}\), it was found that the photopeak moves progressively to lower energies on time scales of minutes, eventually stabilizing at \( \sim 60\%\) of the initial peak value. Thus, one ends up with a large flat continuum extending out to the original photopeak energy, on which is superimposed a relatively narrow photopeak centered at \( \sim 60\%\) of the initial photopeak energy. Upon removing the beam, the affected areas were found to recover after about 10 mins. Because of their very low specific activities, the effect was not observed with the radioactive sources.

### 4.1. Spatial responses

The spatial uniformity of the array was evaluated by raster scanning a 20 keV pencil beam of size 50 \( \times \) 50 \( \mu \)m\(^2\), across the entire array with a spatial resolution of 30 \( \mu \)m. Spectra were accumulated for fixed time intervals (3.5 s) at each position on a 52 \( \times \) 52 spatial grid which covered the array. The total count rate above a 3 keV threshold, the peak centroid position and the FWHM energy resolution at each position were determined by best-fitting. The measured spatial distributions are shown in fig. 9, in the form of surface and contour plots - (a) shows the variation in count rate profile, (b) the fitted centroid of the photopeak, and (c) the resolving power, i.e., \( E/\Delta E \). From fig. 9, we can see that all spatial distributions are uniform over the surface of each pixel and over the entire array. In fact, the average non-uniformity seen in each distribution is consistent with the expected statistical variations, i.e., \( a) = 3\% \), \( b) = 0.3\% \) and \( c) = \sim 15\% \). The latter is limited not by statistics, but by the robustness of the fitting algorithm. The spatial distribution also reflects the uniformity of the electron \( \mu \tau \) product throughout the array. The fact that the distributions are so uniform, is borne out in fig. 10, in which we show the sum of all 2704 spectra accumulated across the
Fig. 9. The spatial responses of the array, mapped at HASYLAB using a $50 \times 50 \, \mu m^2$, 20 keV X-ray beam. (a) shows the variation in count rate profile, (b) the fitted centroid of the photopeak, and (c) the resolving power, i.e., $E/\Delta E$. These distributions were derived from spectra accumulated at 2704 positions across the array.
array during the scan. We see that although the 20 keV peak is broadened to 6.4 keV FWHM, it is clearly resolved and well separated from the noise floor. The width of the peak is believed to be due to a combination of gain shifts induced by polarization effects, the intrinsic spread in pixel resolutions, summed noise and the inherent variations in preamplifier gains. The large noise floor (~ 7 keV) is a consequence of the linear fan-in, for while it allows us to digitize all 9 pixels through a single analog channel, it also sums the individual noise contributions from all 9 channels. The flat continuum on which the peak sits was found to be due to partial energy-loss spectra accumulated in the inter-pixel gaps. To illustrate this, Fig. 10 also shows an individual spectrum recorded in the inter-pixel gap between pixels 2-3 and 1-3. This spectrum was renormalized to “fit” the continuum. For completeness, we also show a spectrum taken at the center of pixel 2-3.

![Graph](image)

Fig. 10. The sum of all 52 x 52 spectra accumulated during the area scan. The FWHM energy resolution is 6.4 keV. The width of the peak is largely due to polarization effects and to inherent differences in the preamplifier gains. For comparison, we also show two individual spectra; one accumulated at the center of pixel 2-3 and the other at a point within the inter-pixel gap between pixels 2-3 and 1-3. This spectrum has been artificially scaled to the continuum for illustrative purposes.

5. Discussion and conclusions

Whilst the overall spectral performance of the array is limited, its optimized single pixel performance is nevertheless close to CdZnTe and this is very encouraging.
Coupled with its high density, this material has great potential as a gamma-ray spectrometer and specifically in those applications requiring very high quantum efficiencies in the hard X-ray and low-energy gamma-ray bands. The fact that it can operate near room temperature has important consequences for a number of applications where power, mass and volume are at a premium (e.g., planetary X-ray fluorescence imagers, intra-operative surgical probes), alleviating the need for complex and expensive cryogenic systems (as in the case of Ge or Si detectors). Resolution data taken with planar detectors [10] indicate that the present material is limited by low charge collection efficiency due to trapping. In particular, the tailing on higher energy lines is indicative of poor hole transport (e.g., fig. 8). Because of the purity of the base material, the trapping center most likely arises from Frenkel defects induced during mechanical processing. This effect is exacerbated by the high dielectric constant of TlBr, which ensures a low energy of defect formation. The source of the defects is believed to be a direct consequence of the relative softness of TlBr compared to other materials (Knoop hardness=12 kg mm$^{-2}$ as opposed to 750 kg mm$^{-2}$ for GaAs and 1150 kg mm$^{-2}$ for Si). Any mechanical treatment (i.e., cutting, lapping and polishing) generates a high concentration of intrinsic structural defects by local plastic deformation. This results in higher leakage currents and increased trapping. The depth of these defects can be surprisingly large (up to 1 mm) and so the effects should be more pronounced in pixel rather than the planar detectors. The spectral performance of the present array could be improved substantially if higher biases could be applied to all pixels and we are currently reviewing our fabrication techniques to reduce all mechanical processing. With better base material and fabrication techniques, the remaining deleterious effects of low CCE and hole trapping could then be attacked by careful geometric design of the pixels. Such an approach should allow us to move towards Fano limited spectroscopic performance.

5.1 Applications in nuclear medicine.

TlBr is relatively unique amongst semiconductors in view of its very high density and stopping power. In fig. 11 we show the calculated efficiency of the detector, which still has a usable efficiency of ~10% at 500 keV. The lowest energy of operation is set by the leakage current at ~3 keV. Such a wide dynamic range is ideally suited for an increasingly new range of applications, such as isotopic measurements for environmental redemption, gamma-ray astrophysics and nuclear medicine, where small size and large stopping power are highly desirable attributes. The fact that TlBr has a good response to gamma-rays in the nuclear transition region makes it particularly well suited for use in intraoperative, radio-guided surgical probes.
For nuclear medicine applications we should consider an efficiency of, say, 30% as the lowest acceptable, because of patient dose issues. Therefore, the current detector has an effective upper energy range of ~ 250 keV. In fig. 11, we also show efficiency curves for 2.5 mm, 5 mm and 10 mm thick TlBr as well as the efficiency for a 3 mm thick CdTe detector (the thickest material currently available for surgical probes [14]). We note that below 200 keV, 1 mm of TlBr is equivalent to 3 mm of CdTe. However, with reference to fig. 11, it is clear from the positions of the 5 most common radionuclides used in nuclear medicine, that a thickness of at least 2.5 mm of TlBr should be considered a requirement\(^1\). Currently CdZn and CdZnTe probes do not exceed 3 mm and so at the present time, this energy range is covered by using more than one probe, with the highest energies monitored using a scintillator/photodiode combination.

![Efficiency vs Energy](image)

Fig. 11. Calculated efficiency of the array. For comparison, we also show efficiency curves for 2.5 mm, 5 mm and 10 mm thick TlBr and well as the efficiency for a 3 mm thick CdTe detector. This is the thickest material available in surgical probes currently available [14]. The line energies of the 5 most common radionuclides used in nuclear medicine are shown.

For sentinel node detection, the present array is too small in area, although its thickness is comparable to commercial products. Since the size of the sentinel node can be of the order of several tens of mm\(^2\), an active area of about 100 mm\(^2\) would seem prudent. The minimum number of pixels considered should 4 in a 2 × 2 array

\(^1\) since the efficiency for detecting 356 keV γ-rays from \(^{131}\)I is ~30%
because 1) the tumor itself can extend over the area of the probe and 2) subdividing the active area in this way will allow a more accurate location of the peak activity using bi-directional gradient techniques. These methods have the added advantage of improving the signal to noise for very small lesions, by making the probe less sensitive to “take-up” radiation from the rest of the body or “shine-through” radiation from the primary injection site. In fact, hot-spots, of volumes of a few tens of cubic mm\(^3\) or less, could be detected. However, the goal should be not only to locate the node but also to image the surrounding area. Therefore, the number of pixels should be large enough to locate the sentinel node with good sensitivity and have good enough spatial resolution to map the distribution of possible carcinomas.

The divergence of the induced charge distribution sets a natural limit to the smallest size of the pixel and therefore the maximum number of pixels in the probe. Obviously, the smallest pixel size should be sufficiently large to accommodate all of the liberated charge. The charge transport is governed by combination of drift and diffusion. In the simplest case, when the drift velocity is sufficiently large, diffusion will not significantly change the charge motion along an axis normal to motion. In practical detectors, diffusion causes the charges of different sign to fill two, back to back, aligned cones with their heads at the absorption site and bases facing the detector electrodes. Depending on the charge carrier, the largest base area of the cones occurs for the shallowest or deepest X-ray absorption. Based on a simplification of a solution to the Laplace equation, which includes diffusion, the minimum pixel size can be shown to be,

\[
\varepsilon_{\text{min}} = 4L \sqrt{\frac{k_b T}{eV_0}},
\]

where, \(k\) is the Boltzmann constant, \(T\) is the temperature, \(V_0\) is the applied bias and \(e\) is the electronic charge. Making pixel sizes smaller than this dimension will not improve spatial resolution because charge divergence will cause a response in neighbouring pixels as well. It is worth noting that minimum pixel size does not depend on carrier mobility but only on ratio of ambient temperature to the applied voltage. If we now consider a detector thickness, \(L\), of 2.5 mm (which will give an efficiency of \(\sim\)30\% for the highest energy photons from \(^{131}\)T), then \(\varepsilon_{\text{min}}\) the minimum pixel size would be 50 \(\mu\)m, assuming \(T = 300\) K and \(V_0 = 200\) V. In this case, the number of pixels would be over \(10^4\)! However, the ratio of \(d/L\) would be \(\sim 0.02\), which is significantly less than the optimum value of about 0.25 derived by Eskin et al. [15]. Using this ratio, the pixel size will be 625 \(\mu\)m. Now assuming an inter-pixel gap of 100 microns and a 200 \(\mu\)m guard-ring surrounding the array, the array would be of size 13 \(\times\) 13 pixels. Such an array could be instrumented by flip-chip bonding to an ASIC, for example, one based
on the MEDIPIX design [16]. From section 3.1, we can conservatively estimate at least a 10 fold improvement in peak to tail ratio with this geometry over a conventional monolithic design.

In summary, the attributes of TiBr make it an ideal material for the production of intra-operative probes. By using a segmented or pixelated anode design and tailoring the geometry to promote near-field effects, most of the negative material attributes normally associated with TiBr (e.g. poor hole transport) can be largely negated.

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