# SEMICONDUCTOR PIXEL DETECTORS

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**Abstract:** Semiconductor pixel detectors were originally developed for particle physics experiments as a logical development from silicon microstrip detectors, offering the potential for high spatial precision, two dimensional location of ionising charged particle trajectories. The development became practical, as with microstrip detectors, only with the availability of suitable VLSI read-out electronics and reliable (and affordable) interconnect technology, ("flip-chip" bonding).

Pixel detectors have also been studied more recently as imaging devices, particularly for X-rays in medical and non-destructive testing applications, and in synchrotron radiation beams.

In the following, a description is given of the evolution and current state of development of pixel detectors for all of these applications. Reference is made to both monolithic and hybrid semiconductor pixel detectors, considering not only silicon, (crystalline and amorphous), but also alternative semiconductor materials. The performance and limitations of current read-out electronics and bonding technology for hybrid detectors are discussed, together with the relative merits of charge integrating versus photon counting read-out for X-ray imaging applications. The paper concludes with an outline of potentially valuable future development possibilities.

# Polprevodniški detektorji s slikovnimi elementi

**Ključne besede:** polprevodniki, detektorji pikselski, upodabljalniki, grafika računalniška, preskušanje nedestruktivno, stanje razvoja, HEP fizika energij visokih, CCD naprave z nabojem sklopljenim, APS senzorji aktivni pikselski, ROIC vezja integrirana bralna, LHC trkalniki hadronski veliki, medicina, fizika delcev

**Izvleček:** Polprevodniški detektorji s slikovnimi elementi so bili sprva razviti za potrebe eksperimentov fizike delcev kot logični razvoj iz mikropasovnih detektorjev, saj so ponujali visoko prostorsko ločljivost in možnost dvodimenzionalnega določanja poti ionizirajočih nabitih delcev. Toda razvoj je imel praktične rezultate šele, podobno kot v primeru mikropasovnih detektorjev, z izvedbo ustrezne VLSI čitalne elektronike in zanesljive (in dovolj poceni) povezovalne tehnologije ("flip-chip" bondiranje).

Detektorje s slikovnimi elementi so zadnje čase precej študirali kot možne detektorje slike, zlasti za rentgenske žarke za uporabo v medicini in za nedestruktivno testiranje, oz. v sinhrotronskih žarkovnih linijah.

V prispevku podajam opis nastanka in trenutnega stanja razvoja detektorjev s slikovnimi elementi za vse navedene rabe. Omenjam tako monolitne kot hibridne izvedbe detektorjev ne samo na siliciju (kristalnem in amorfnem) ampak tudi na alternativnih polprevodniških materialih. Obravnavam delovanje in omejitve sodobne čitalne elektronike in tehnologije bondiranja hibridnih detektorjev ter primerjam relativne prednosti odčitka integriranega naboja proti direktnem štetju fotonov pri slikanju z rentgenskimi žarki. Prispevek zaključim s pregledom razvojnih možnosti v bodočnosti.

## Introduction

Semiconductor pixel detectors were initially developed for high energy physics applications because of their low noise, high spatial resolution and two dimensional position information /1-10/. Their potential for X-ray imaging applications was soon realised, because of their higher energy resolution, high density, good spatial resolution, speed of response and increased counting rate capabilities /11-14/.

Pixel detectors may be broadly categorised into two broad varieties: Charge Coupled Devices (CCDs) and Active Pixel Sensors (APS), the latter being sub-divided into monolithic devices /7-9/ and hybrid detectors /2/. Early attempts to fabricate monolithic detectors were faced with problems due to the many stages of processing required, (typically over a dozen), potentially conflicting requirements for optimising the detector and the read-out components of the detector and associated problems of low yield of useful devices. More recently, large area (~ 25 x 35 mm$^2$) silicon CMOS ROIC have been developed for imaging applications /13/, and offer considerable promise as relatively low cost detectors, especially when coupled to scintillator layers to enhance their X-ray absorption efficiency. A practical upper limit on the area of these devices is set by the size of the reticle used in the silicon foundries which produce the chips. In the case of hybrid APS, the detector and read-out integrated circuit (ROIC) are fabricated on separate wafers and connected through "flip-chip" bump-bonding, using approximately spherical bonds of gold /14/, indium /15/ or solder /4/. This technology allows the separate optimisation of detector and ROIC and also provides greater flexibility in the choice of active medium for the former. With the trend towards ever smaller feature sizes in silicon processing technology, it becomes possible either to incorporate more sophisticated processing features into each pixel of the read-out chip, (making "smart" chips), or alternatively to compress the read-out area per pixel, giving higher spatial resolution capability /16,17/. A more detailed, (but not comprehensive), description is given below of the continuing evolution of pixel detector read-out circuits within the microelectronics groups at the

CERN laboratory, (as part of the RD19 detector R&D collaboration /18/), the Rutherford-Appleton laboratory (as part of the UK Technology Foresight project "IMPACT" /14/ ) and elsewhere /13,26/.

In parallel with developments in read-out circuits, active investigations continue into alternatives to crystalline silicon as the detector medium. Large area, (~A4 page size) imaging panels based on amorphous silicon are now available commercially, for example /19,20/. A brief review is given below of the status of this technology and of GaAs, diamond, Cd(Zn)Te and other, more unconventional detector materials.

## The LHC Pixel Detectors, (ALICE, ATLAS, CMS and LHCb)

Pixel detectors are destined to play a crucial role in the experiments now under construction for physics using the Large Hadron Collider at the CERN laboratory /26/. They should provide very high precision location, (~10 $\mu$m), of charged particle tracks emerging from the collision of the intersecting proton beams, and help to select potentially interesting, rare events among the large backgrounds through the identification of secondary vertices from the radioactive decay of short-lived, (particularly charm or beauty) particles. They have to operate in the most hostile radiation environment of any of the detector components, and are expected to be subjected to (1 MeV neutron equivalent) fluences of, typically, 1-2x10$^{15}$n/cm$^2$ during ten years of LHC operation.

In the case of the ATLAS pixel detector, for example, each sensor is a 16x60 mm$^2$ silicon wafer covered by an array of 50x400 $\mu$m$^2$ pixels, bump-bonded to an assembly of 16 front-end chips, each of 18x160 cells arranged in 9 double columns. Every read-out cell contains a preamplifier and discriminator, facilities for storing leading and trailing edge time stamp information and control circuitry for selection and masking. The 2228 modules in the overall pixel detector, (barrel plus end-cap disk sections), then correspond to 140 million channels in a cylinder 1.6 m long, 0.5 m in diameter, as shown in Figure 1. Extensive R&D activity has been directed to improving the high voltage stability of the sensors, particularly against micro-discharge effects, e.g. through careful design of guard ring structures /59/.

Other obvious practical problems with such an array include the provision of suitably stable mechanical support structures, radiation damage effects in sensors and read-out electronics and the power consumption in the read-out electronics. This amounts to more than 14 kW in the detector volume, in the ATLAS case, and demands careful attention to cooling of the assembly.

### Improving the radiation hardness of silicon detectors

In spite of significant advances in the understanding of how radiation-induced defects can influence the performance of silicon pixel detectors, there is still considerable scope for further improvements, in particular with a view to the needs of high precision vertex detector layers for future high luminosity colliders, where the radiation doses may be even worse than those expected at the LHC. Three approaches have recently been made to the problems: (a) "defect engineering" of the basic silicon wafers, e.g. by introducing higher levels of oxygen dopant atoms /32/, (b) so-called "3-D" detectors /33/ and (c) cryogenic operation of silicon detectors, based on the so-called "Lazarus Effect" /34,35/.

Figure 3 illustrates the difference between conventional detectors and 3-D detectors. The former are based on planar technology, with electrodes on either face of the silicon wafer, while the latter employ a regular matrix of cylindrical electrodes drilled through the wafer, e.g. by reactive ion etching, laser drilling or light-enhanced chemical etching techniques.

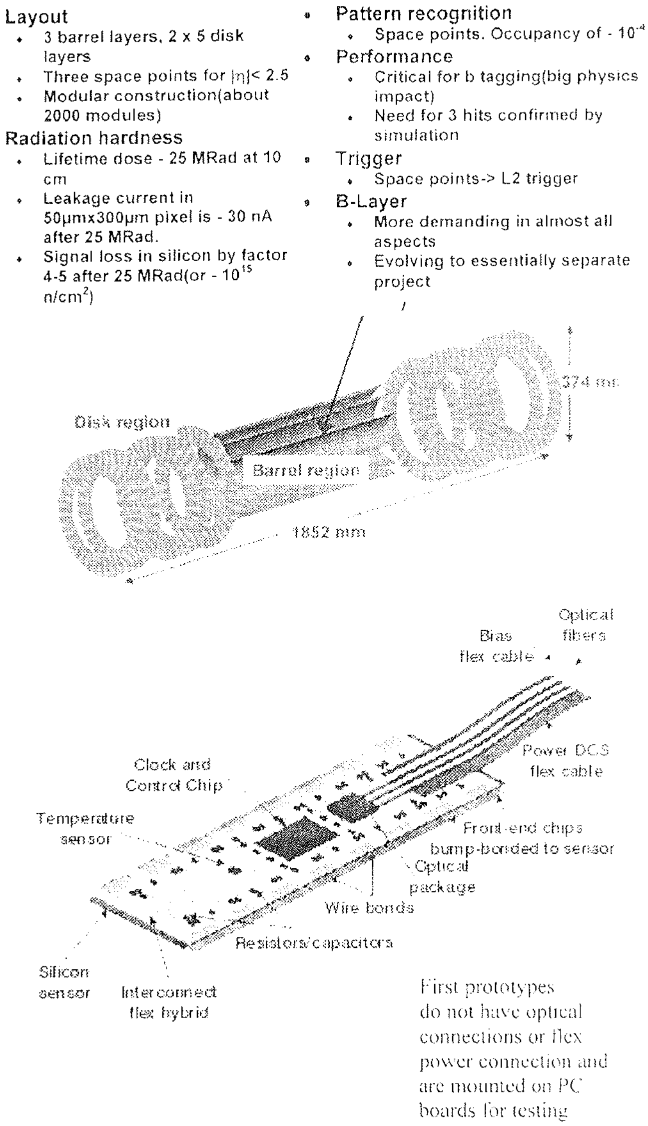



*Fig. 1. Structure of the ATLAS pixel detector array, consisting of 2228 silicon pixel modules, mounted in a lightweight carbon fibre support structure. Each module consists of 18 x 160 cells of 50x400 µm$^2$ pixels, flip-chip bump-bonded using low temperature solder to custom read-out chips, for a total of around 140 million read-out channels.*

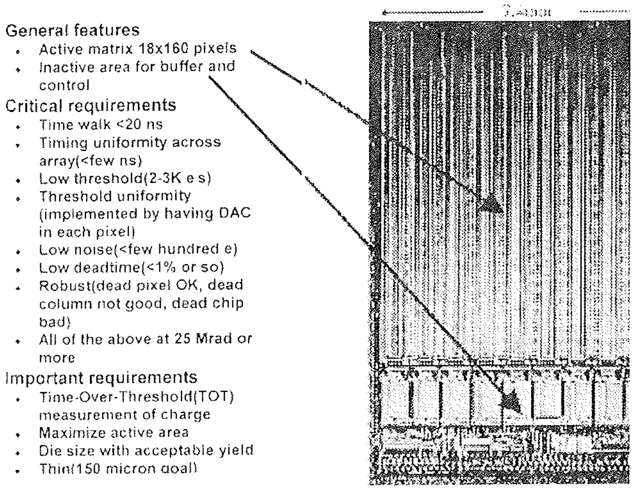



*Fig. 2. An ATLAS pixel module, illustrating the flip-chip bonding used to connect the detector pixels to the corresponding charge sensitive read-out electronics elements.*

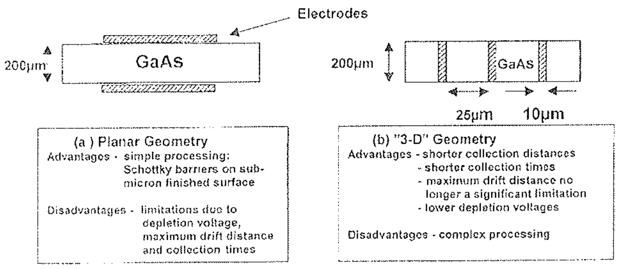



*Fig. 3. Comparison of the structure of a conventional "planar" detector and the "3-D" structure proposed and prototyped in silicon by Parker et al. and in GaAs by Bates et al. /33/.*

In such a detector, the electrons and holes created by ionising radiation drift transversely to the collecting electrodes and, providing that this distance is comparable with the mean free path before charge carrier trapping, the loss of signal due to radiation damage is tolerable, while the speed of response should be excellent. The predicted full depletion voltage for this geometry is much less than for the conventional, planar approach, and this has recently been verified experimentally, as shown in Figure 4, before and after exposure to "ten years of LHC" equivalent radiation doses. Further development of this exciting new approach is now being pursued actively in a number of laboratories.

Following the discovery that highly irradiated silicon diode detectors could be "resurrected" by operating them at liquid nitrogen temperatures /34,35/, an extensive research programme has been undertaken within the RD39 R&D collaboration /36/. It now appears that it is sufficient to run at temperatures around 120-130K to achieve similar results. An additional benefit of this mode of operation of silicon detectors is that leakage currents are reduced to essentially negligible levels, opening up the possibility of using less expensive, and possibly larger area silicon wafers for detector fabrication. The need to fill the charge trapping centres so as to render them inactive in subsequent charge carrier transport means that forward bias operation is favoured, as shown in Figure 5.

## Read-out Circuits

### (a) ASIC"s for high energy physics and medical X-ray imaging applications

#### The Omega series

The Ω 3 ROIC is the latest in a series of ROIC which were initially developed within the CERN-sponsored RD19 R&D collaboration to be hybridised with a matching array of silicon detectors for high energy applications /3,4,8,16,18/. Consisting of a matrix of 2048 (128x16) pixels of 50x500 $\mu m^2$, it has been used successfully in the construction of a pixel detector telescope for a heavy ion experiment at the CERN /25/. Figure 6 illustrates the ability of this telescope to resolve the large multiplicity of charged particle tracks emerging from high energy lead-lead collisions.

The Ω 3 performance as an X-ray imaging device with GaAs as the detecting medium was reported in /28/. The resolution along the small dimension was found to be comparable with deep depleted CCDs and even better than CCDs with a scintillator coating. An analysis of the Modulation Transfer Function showed 10% modulation at the limiting Nyquist frequency (~10 line pairs per mm).

A continuation of this programme characterised the X-ray imaging performance of an Ω 3 hybrid APS using silicon as the active medium /29/, concentrating on the signal-to-noise ratio of the sensor. In Figure 7a), the flood image after uniform exposure to 60kVp X-rays can be seen for an exposure time of 3.2 sec, corresponding to an incoming fluence of approximately 6.4 x $10^9 cm^{-2}$. The response of the detector is uniform apart from a small number of pixels which show no response, due to bad bonding, at the upper left and lower right corners. The response as a function of exposure time (or number of incoming photons) can be seen from the sensitometric curve, Figure 7b). The response is linear across the whole dynamic range, with neither "fog level" at low fluences nor "blooming" at high fluences. This is an inherent characteristic, and one of the main attractions of photon counting systems, compared to charge integrating devices.

The extremely high dead time fraction of 0.9993 was expected, since the read-out chip is synchronously read out, i.e. triggered by a DAQ clock which is uncorrelated with the arrival of the X-rays. Each pixel is active only for a period equal to the width of the trigger pulse, $\leq 4\ \mu s$, for every read-out cycle of 8.3 ms, so that the active fraction is around $5 \times 10^{-4}$.

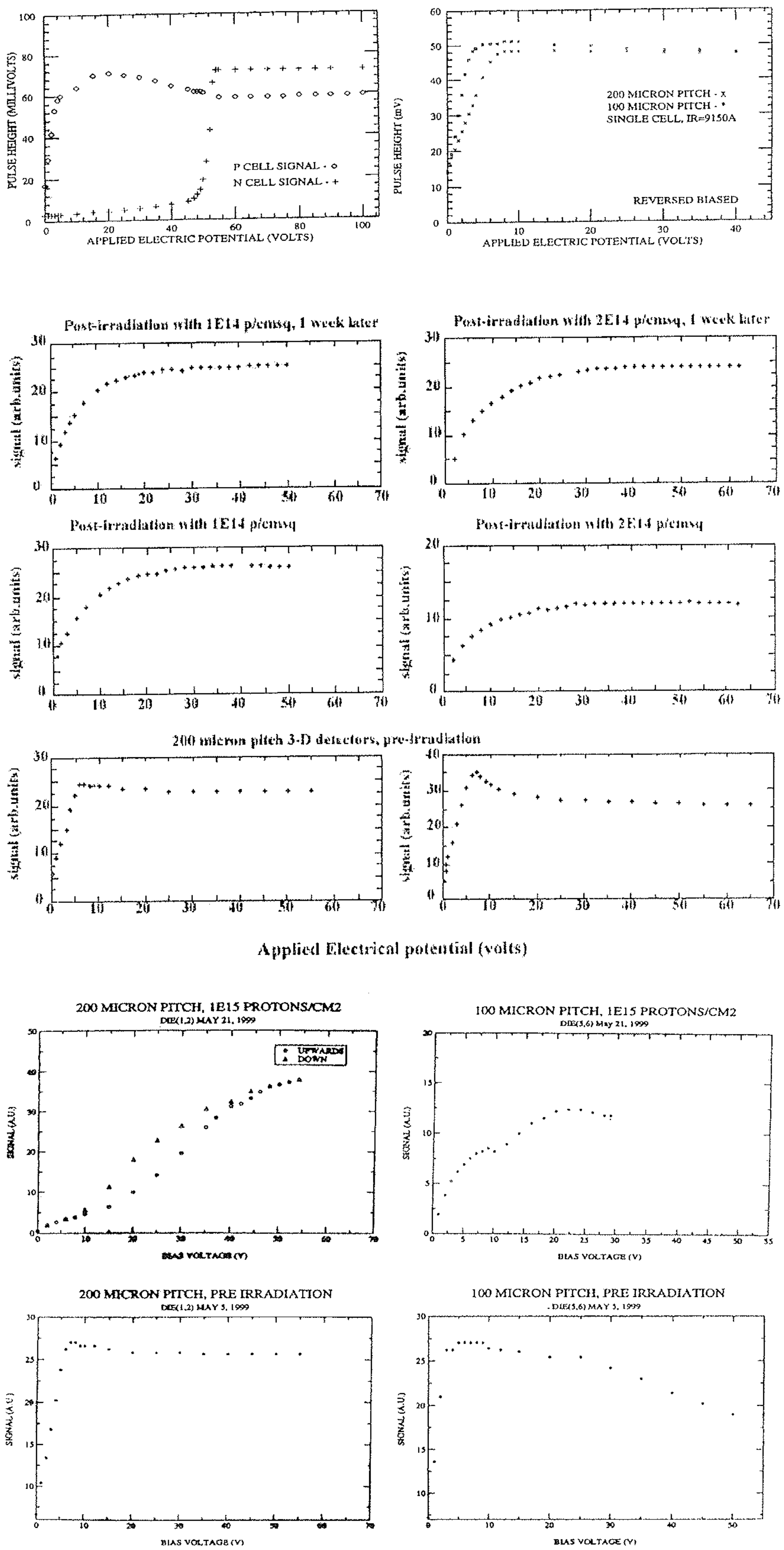
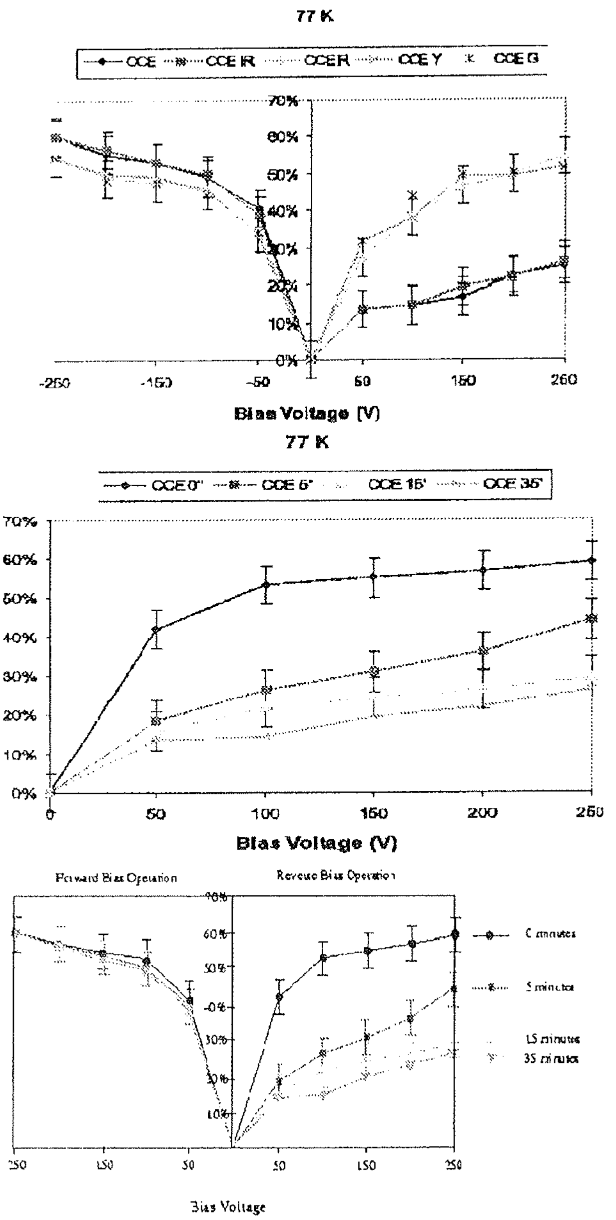



*Fig. 4. The response of prototype "3-D" silicon detectors to stimulation by an LED light source, as a function of the applied bias voltage, (adapted from ref./33/). The lower parts of the figure illustrate the deterioration of the signal after irradiation with 55MeV protons to fluences corresponding approximately to the expected ten year exposure at the Large Hadron Collider. The effect of partial annealing of the radiation-induced crystal defects is illustrate by the change observed one week after the irradiation.*




- For the first time, a full, realistic detector module, has been irradiated to $4x10^{14}$ p/cm$^2$ and operated at cryogenic temperatures to investigate the Lazarus Effect.
- Cryogenic operation with a relatively low depletion voltage gives a dramatically improved transient performance of the irradiated detector.
- To get the improvement you must go below ~130K.
- No pathologics in resolution or landau distribution observed
- Recovery has a time dependence, and degrades after ~15 minutes
- The degradation can be controlled with Charrge Injection.

*Fig. 5. Charge collection efficiency of heavily irradiated silicon detectors operated at cryogenic temperatures (at or below 130 K), as a function of applied bias voltage. Also shown is the influence of irradiating the detector with visible light of differing wavelengths. The lower graph shows the variation with time of the collected charge signal in reverse bias, in contrast with the relative stability with time when forward bias is used.*

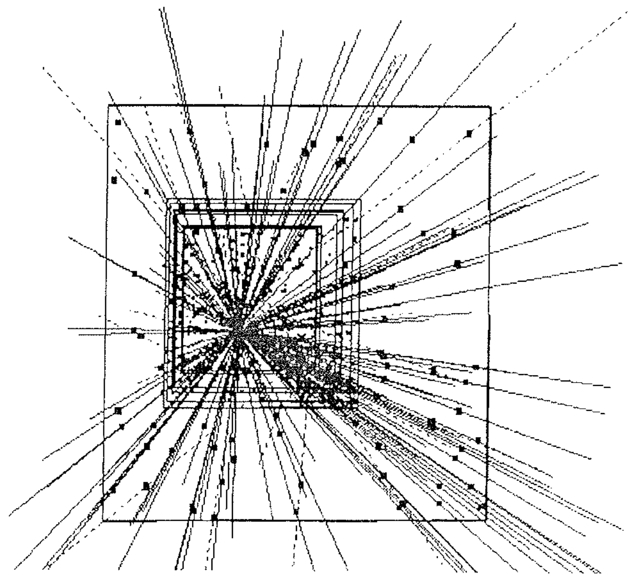


*Fig. 6. High multiplicity charged particle tracks resulting from 200 GeV Pb-Pb collisions were successfully reconstructed using a five layer telescope of silicon pixel detectors, read out using the Omega3/LHC1 read-out integrated circuit developed by the CERN Microelectronics Group (cf. Ref. /18/).*

Photon limited noise performance in the image is found only for low exposure times, Figure 7c), while at higher exposure times a rather linear dependence with the number of incoming quanta is observed, for reasons which are not yet completely understood, although a more detailed study of the SNR distribution across the pixel matrix, reveals "good" and "bad" areas. The main variation between these areas is in their noise behavior, Fig. 7c), the good areas displaying almost photon limited high values of signal-to-noise ratio while the bad areas deviate from Poisson statistics, and can be almost linear in their dependence on exposure time in the worst cases.

## (b) Charge Integrating Circuits

The requirement in applications such as mammography for large area pixel arrays has led to the development of amorphous silicon panels, using thin film transistors to read out the charge signals created by absorbed X-rays /19,20/. These are now beginning to compete with more traditional film-screen systems in terms of efficiency and spatial resolution and can be fabricated at an affordable cost.

Among the earliest pixel imaging systems, the performance of the silicon CCD, typically with a coating of scintillator to enhance the efficiency for X-ray absorption, is still among the best available commercially. The technology is already very mature and the detailed characteristics of the detectors well under-stood /21/. There have been promising developments very recently /22/ towards production of CCD"s based on epitaxial GaAs for dental X-ray imaging, (following pio-

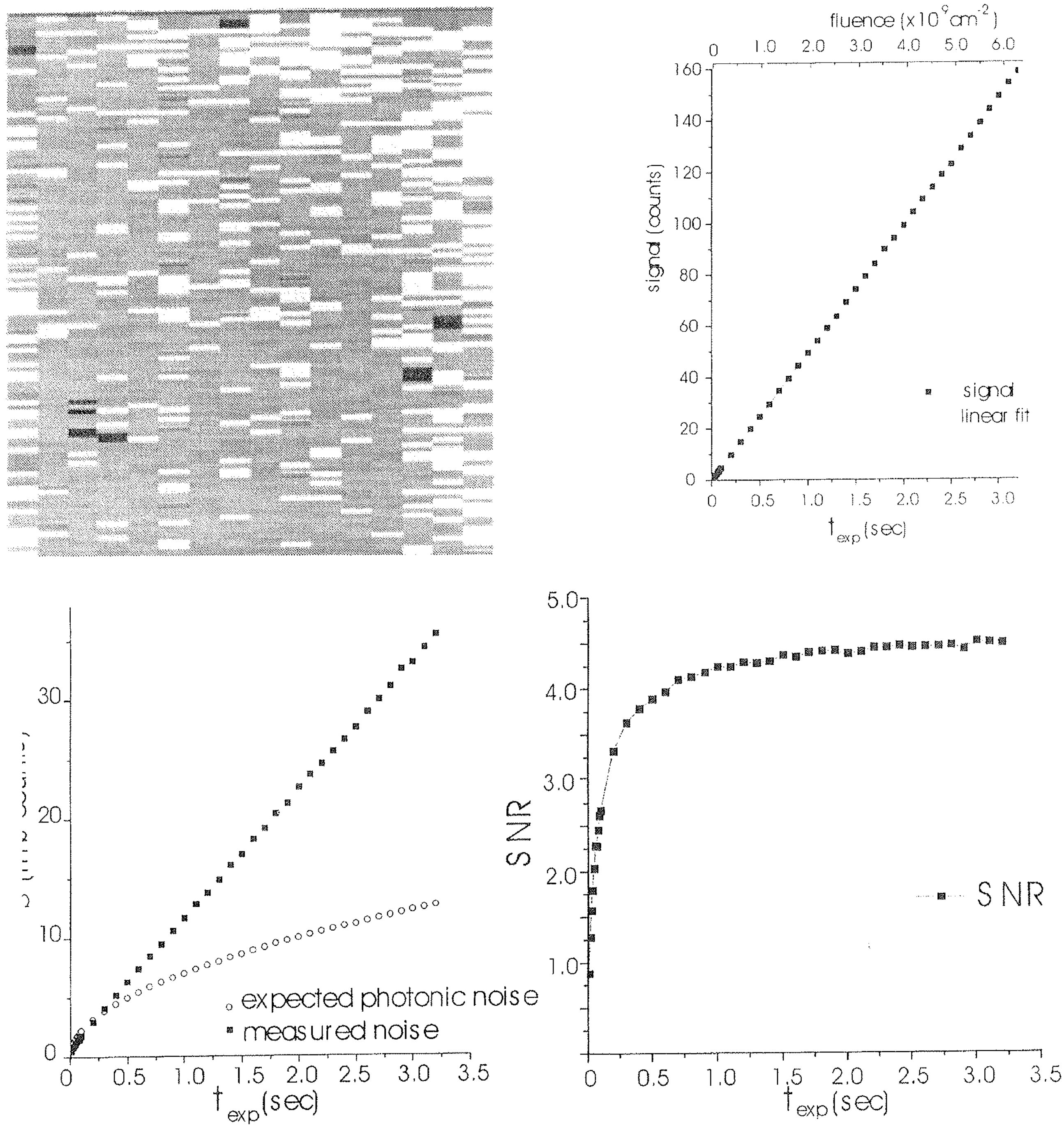



*Fig. 7. Results of X-ray imaging tests of silicon pixel detectors bump-bonded to Omega3/LHC1 ASICs, showing (a) the recorded signal "hits" in a "flood" image (uniform illumination of all pixels in the 16x128 element array); (b) linearity of response with fluence over the whole dynamic range; (c) the variation of the noise contribution to the pixel count as a function of the dose, showing fluctuations consistent with Poisson statistics only in limited regions of the detector. The variation with fluence of the overall signal-to-noise ratio is shown in (d).*

neering work on GaAs analogue shift registers at TRIUMF /23/).

The choice of GaAs instead of silicon is motivated by its higher absorption of the 30-40 keV X-rays which are typical in this area of application.

Within the same project, 35 $\mu$m pitch GaAs pixel detector arrays have been bump-bonded, using indium bumps, to a 320x240 pixel array, charge integrating read-out circuit (ROIC) which was initially developed for an infra-red imaging system /24/. While prototype detectors of this type revealed inhomogeneities in the response due to crystal defects in the Liquid-encapsulated (LEC) substrate GaAs /25/, it was possible to apply simple correction factors to the signal from each pixel to correct for these effects, as shown in Figure 8. The quality of the corrected image compares well with that obtained with a commercial silicon CCD/scintillator system.

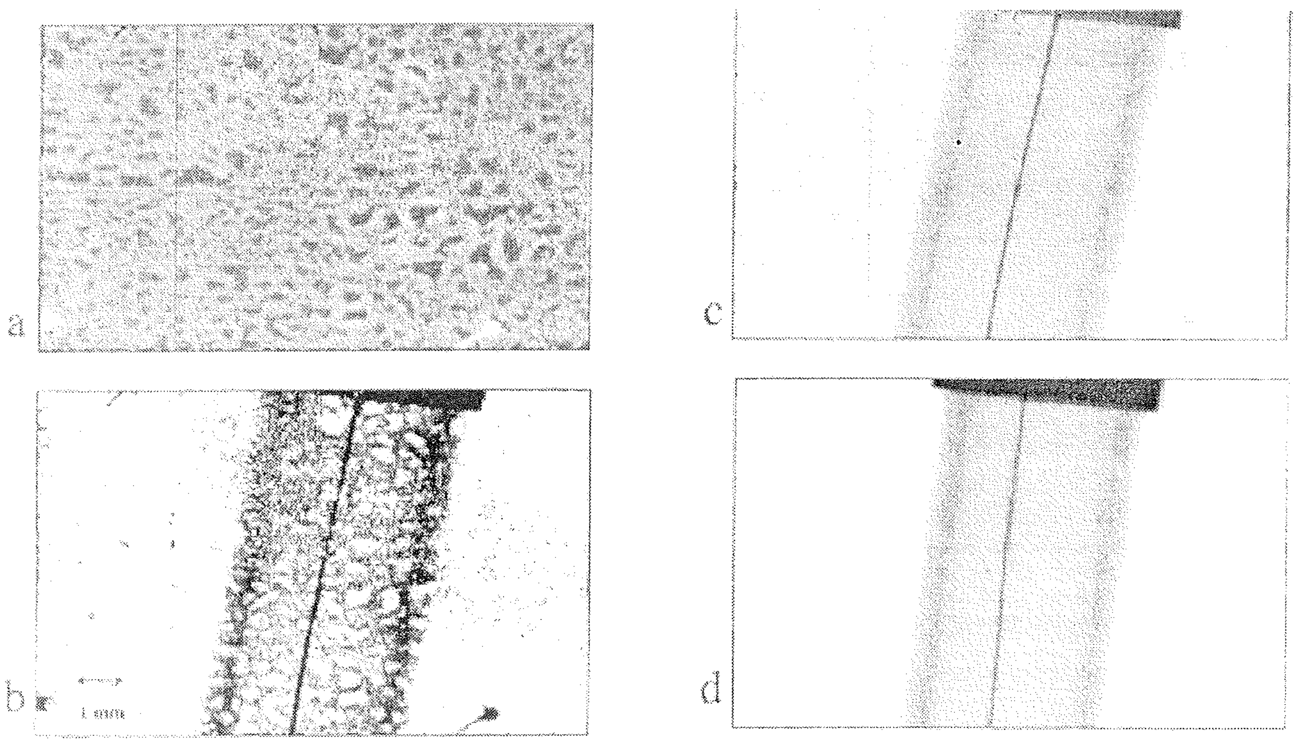



*Fig. 8. X-ray images obtained with a 200 μm thick LEC GaAs pixel detector array using a standard dental X-ray source. The 38μm square pixels in the 320x240 element array were bump-bonded using indium bumps to a charge-integrating read-out circuit developed originally for infra-red imaging applications, (cf. Ref. /24/). The micro-inhomogeneities in the GaAs substrate material are clearly visible in the response to a "flood" image (uniform illumination of the detector array), shown in (a), and in the "grainy" image of a fuse wire shown in (b). Using a simple multiplicative factor to correct the response on a pixel-by-pixel basis resulted in the much improved image of (c ), to be compared with the image in (d) obtained by a commercial dental X-ray imaging system based on a scintillator coated silicon CCD.*

## (c) The MEDIPIX Photon Counting Chip (PCC)

First images have recently been obtained from the new ROIC in the same series, the MEDIPIX /29/ bonded to a GaAs detector. This chip is based on the Ω 3 but has single photon counting capability and individual pixel comparator threshold adjustment to enable compensation for processing variations across the chip. It consists of a 64 x 64 matrix of cells with 170 μm x 170 μm pixel dimensions. Each pixel contains a 15-bit counter, and a 3-bit adjust for threshold fine tuning. The dead time has effectively been eliminated due to a shutter based acquisition method, and the matrix can be read out in 384 μs at 10 MHz. A more uniform background response and improved object contrast is observed with the 3-bit threshold adjust loaded on the read-out chip, as illustrated in Figure 9. The electrical threshold variation improves from ~400 e- to ~80 e- on utilising the threshold adjust /30/.

### Alternative materials to silicon

While silicon has always been the first choice for pixel detector fabrication, because the technology is very well established and readily available, its suitability for X-ray imaging is limited by the rapid decrease in its linear absorption coefficient for X-ray energies above about 20 keV, as illustrated in Figure 10. This figure also shows the relative gain to be expected at higher energies from GaAs semiconductor pixel detectors, which have been the subject of rather intensive investigation in recent years /40-42/. The micro-inhomogeneities in widely available, relatively cheap LEC GaAs substrates have already been mentioned. There has therefore been considerable interest in obtaining high quality, thick layers of epitaxial GaAs, hopefully less subject to such inhomogeneity. The excellent energy resolution obtained recently with small, single pad diode epitaxial GaAs detectors by the ESA/ESTEC group /43,44/, illustrated in Figure 11, gives considerable grounds for optimism for the future of this material.

For higher energy X-rays, and for applications such as SPECT and PET imaging, attention has recently been focused strongly on CdZnTe, (CZT), as the detector material /45-47/. An example of a pulse height spectrum obtained with a CZT pixel detector in the form of a 1cm cube, shown in Figure 12, illustrates how electronic processing of the charge signals from the top and bottom electrodes, (essentially due only to the electron transport in this material), can be used to give genuine three-dimensional information on the position of gamma-ray conversion inside the detector.

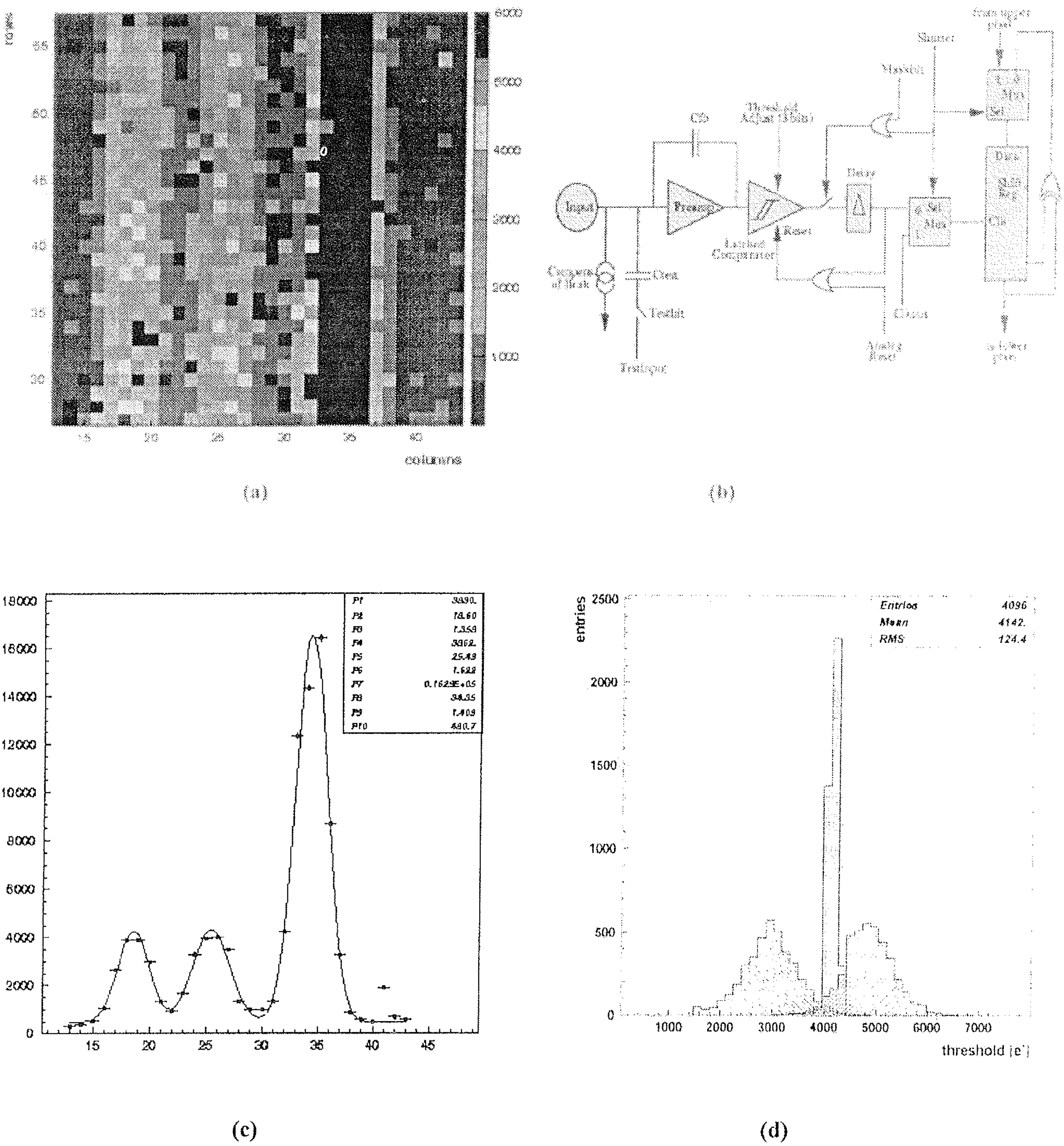



*Fig. 9. a) X-ray diffraction image of a $KNbO_3$ powder sample in a 14 keV synchrotron radiation beam. The projected intensity variations, shown in (c ), match those found by more conventional imaging. The image was obtained with a 64x64 array of 170 μm square LEC GaAs pixels, bump-bonded using low temperature solder bumps to the MEDIPIX photon-counting read-out integrated circuit (cf. Ref. /16/). As shown in the schematic (b), each read-out channel incorporates a three-bit comparator threshold adjust with which to correct for process-limited variations from the nominal value across the chip. The histograms shown in (d) illustrate the number of pixels recording "hits" for the extreme values of the threshold voltage adjustment, and the narrow central peak the result of optimising the value on each pixel so as to minimise the spread overall.*

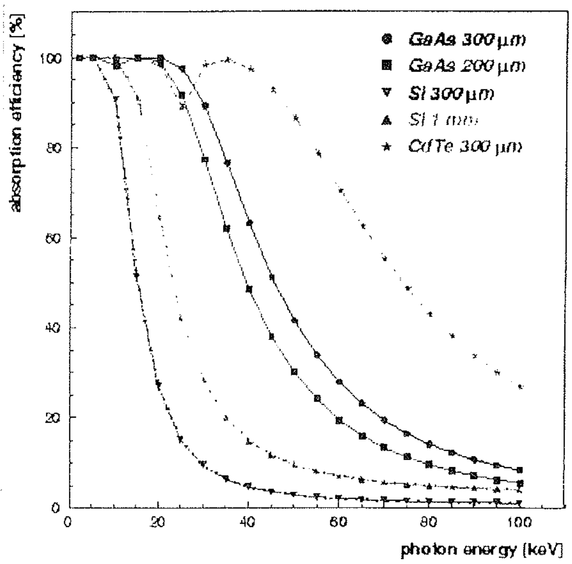



*Fig. 10. Comparison of the X-ray absorption efficiency of different semiconductor layers as a function of X-ray energy.*

For room temperature operation of imaging pixel detectors, low reverse bias leakage currents are clearly desirable, so as to minimise shot noise. Wider bandgap semiconductor materials such as diamond ($E_g$ = 13 eV) and silicon carbide ($E_g$ = 9 eV) have therefore been given serious consideration as bases for pixel detector fabrication, (cf. Figure 13). Diamond detectors have achieved greatly improved performance, in terms of the mean charge collection distance and therefore the charge collection efficiency achievable, over the last two to three years. They have also been shown to be more radiation hard than other semiconductors /48/. Unfortunately they require a much higher energy deposition in the detector than either silicon or GaAs to create an electron hole pair, (13 eV versus 3.6 eV and 4.2eV, respectively), so that the signal charges from diamond detectors are relatively small and demand much better noise performance from their read-out electronics in order to achieve a given signal-to-noise ratio.

There have been attempts recently to investigate silicon carbide as a detector material /49/ because its wide bandgap also offers the prospect of low leakage currents and high radiation resistance and also because its ability to operate at high temperatures could be valuable for certain applications. As yet the technology for fabrication of high quality, large area pixel detectors in this material is still in its infancy, but promises much.

It is worth noting that the development of pixel detector read-out electronics ASIC"s has provided a new method of investigating the homogeneity of the detector semiconductor material. This approach has already proved valuable in characterising CdZnTe crystals, for example /50/, as well as LEC GaAs /25/. Further developments of even smaller pixel elements through deep submicron process technologies may extend these opportunities, although the minimum useful pixel area will presumably be defined eventually by charge sharing among adjacent pixels due to diffusion during transport. Simulation and experimental studies of this charge sharing are now in progress /51/.

## Other applications of pixel detector read-out technology

The successful development of VLSI read-out circuits for pixel detectors in high energy physics has led to a number of spin-off developments. Ring-imaging Cerenkov detectors for the LHCb collaboration are investigating their use inside electron multiplier tubes, for example /27/. Figure 14 illustrates the performance of a prototype device of this type in a CERN test beam. Applications of pixel detector technology for medical applications such as mammography and dental radiology /52/ have already been mentioned and clearly offer very significant reductions in dose to patients.

There is an increasing need for higher spatial precision, large area X-ray diffraction imaging devices in synchrotron radiation beams for applications such as protein crystallography and time-resolved imaging with submillisecond framing times /53/. First demonstrations of semiconductor detector operation in this environment have been given recently /54-56/, but this is a field which promises much for the future. Applications in electron microscopy also seem to offer similar challenges and opportunities for exploitation of new ideas, (e.g. /57/).

Finally, there have been exciting developments in the application of technology from high energy physics to the neurophysiological study of how the retina of the eye functions /58/. If an understanding can be reached of how the retina encodes into the optic nerve the "spike" signals from the wide variety of retinal neuron types, illustrated in Figure 15, there may even be feedback in the reverse direction of new approaches to pixel detectors for high energy physics applications!

## Conclusions

The high level of performance of semiconductor pixel detectors and their associated read-out electronics chips now offers opportunities for their exploitation in a wide range of exciting new application areas from innovative ideas in medicine, non-destructive testing, X-ray diffractive imaging in synchrotron radiation beams and electron microscopes and even neurophysiology, in addition to their original application in high energy physics. At the technological level, definitive demonstrations have yet to be given of the predicted superior performance of photon counting devices over charge integrating devices in X-ray imaging. Further enhancement of the radiation hardness of pixel detectors in experimental particle physics, in particular, is still highly desirable, particularly for the next generation of colliders. Whether this can be achieved using silicon, suitably treated, or using an alternative material such as GaAs, SiC or diamond is a question which can provide excellent opportunities for initiative and innovation on the part of the new generation of detector specialists! Understanding the detailed behaviour of the detector materi-

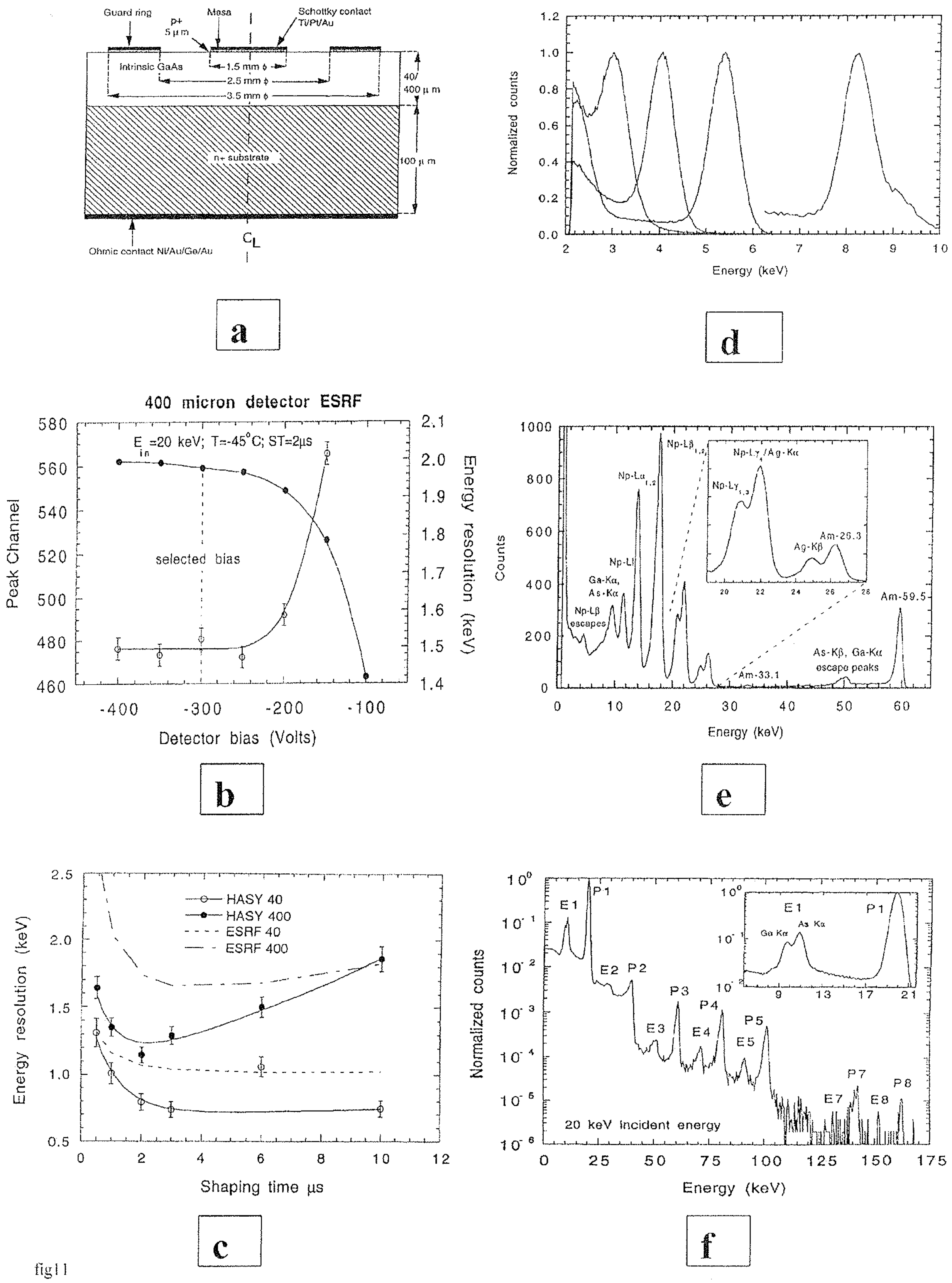



*Fig. 11. X-ray pulse height spectra obtained with high purity epitaxial GaAs Schottky diode detectors by the ESA group (refs. /43,44/). The diode structure is illustrated in (a). The variation of pulse height with bias voltage is shown in (b), and the energy resolution dependence on shaping time in (c). Figures (d), (e) and (f) show, respectively, the response to monoenergetic synchrotron radiation X-ray beams covering a range of energies, the pulse height spectrum from an $^{241}$Am radioactive source and the spectrum from the higher energy harmonics of the synchrotron radiation beam.*

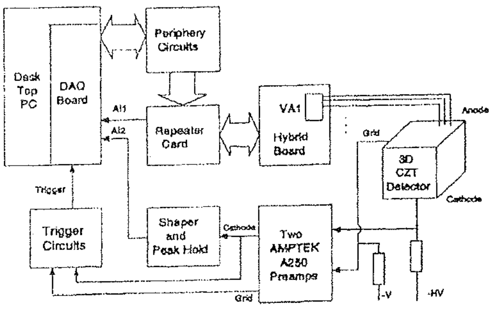



Figure 1: System block diagram.

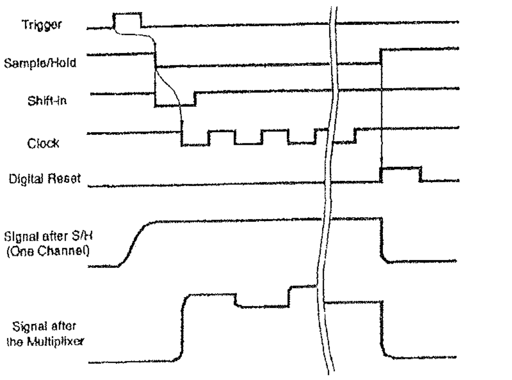
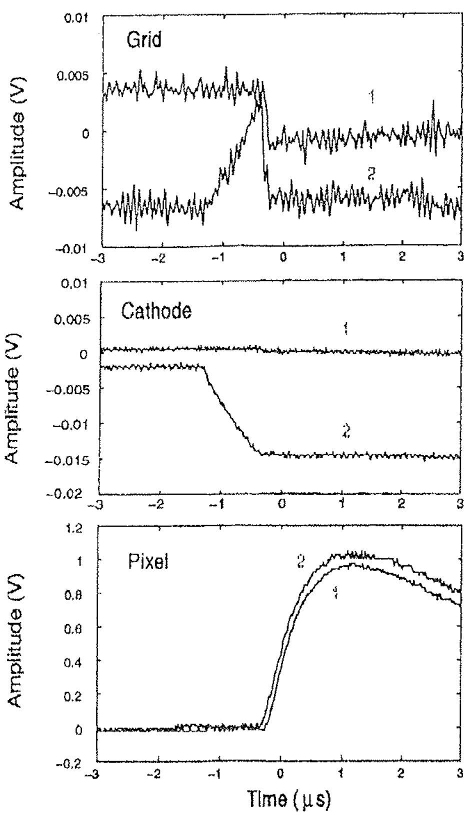
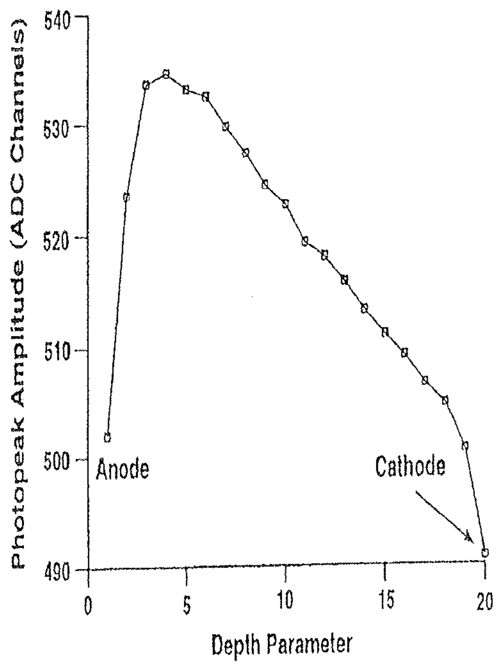



Figure 2: The control signals of the DAQ system and corresponding output from VA1 chip.



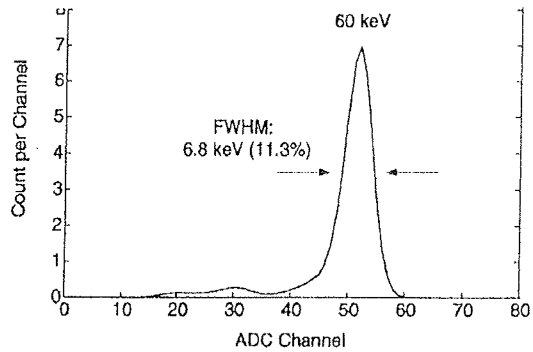




Figure 10: $^{241}$Am spectrum of single-pixel events from the whole bulk of 3-D CZT detector #1.

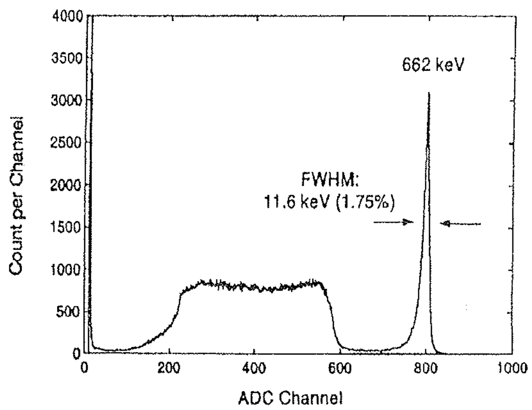
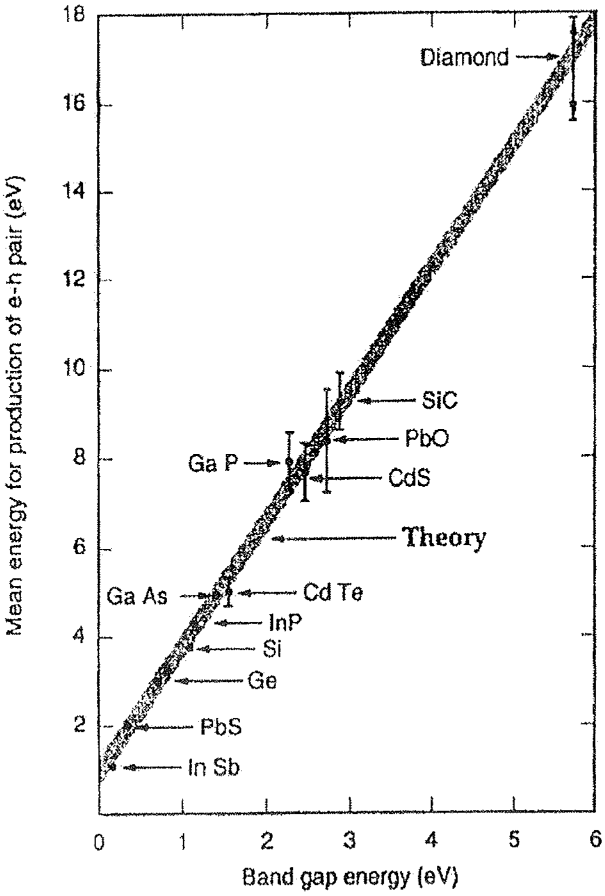



*Fig. 12. Response of a 1 cm cube CdZnTe pixel detector to 667 keV gamma-rays from $^{137}$Cs, obtained by the Michigan Group (cf. Ref. /38/). Suitable pulse shape analysis allows the depth of the gamma-ray conversion point to be measured with an accuracy of around 1 mm.*




Material Properties of
Diamond (D), SiC, GaAs, Si at 293 °K

| Property | D | SiC | GaAs | Si |
|---|---|---|---|---|
| Bandgap [eV] | 5.5 | 3.3 | 1.43 | 1.12 |
| Breakdown Field [V/cm] | $10^7$ | $2*10^6$ | $4*10^5$ | $3*10^5$ |
| Resistivity [Ω–cm] | $> 10^{11}$ | $>10^5$ | $10^8$ | $2.3*10^5$ |
| Intrins. Carrier Density [$cm^{-3}$] | $< 10^3$ | $<10^{10}$ | $10^8$ | $1.5*10^{10}$ |
| Electr. Mobility [$cm^2s^{-1}V^{-1}$] | 1800 | 900 | 8500 | 1350 |
| Hole Mobility [$cm^2s^{-1}V^{-1}$] | 1200 | 20 | 400 | 480 |
| Sat. Velocity [km/s] | 220 | 200 | 80 | 82 |
| Density [$g/cm^3$] | 3.5 | 3.2 | 5.3 | 2.3 |
| Atomic Charge Z | 6 | 14, 6 | 31, 33 | 14 |
| Dielectric Constant | 5.7 | 9.7 | 13.1 | 11.9 |
| Thermal Exp. Coef. [$10^{-6}$/°K] | 0.8 | 4.5 | 6.9 | 2.6 |
| Therm. Cond. [$Wcm^{-1}K^{-1}$] | 15 | 4.9 | 0.45 | 1.5 |
| e-h Creation Energy [eV] | 13-17 | 9 | 4.2 | 3.6 |
| Rad. Length $X_o$ [cm] | 12 | 8.1 | 2.3 | 9.4 |
| Spec. Ion Loss [MeV/cm] | 4.7 | 4.4 | 5.6 | 3.2 |
| e-h pairs /100μm [e] | 3.6k | 4.9k | 13k | 8.9k |
| e-h pairs /0.3% $X_o$ [e] | 7.2k | 15.9 | 9.ok | 24k |

*Fig. 13. Alternative semiconductor bases for detector fabrication are summarised in the graph and table (from ref. /49/).*

als and their behaviour on irradiation is a continuing challenge to semiconductor physicists. Squeezing the greatest processing capability into the smallest area of pixel detector read-out circuitry is driving circuit design technology rapidly towards the deepest of deep submicron process technology available. The other kind of squeeze, on funding levels, encourages ever greater ingenuity in reducing the costs of current technology and in devising radically new interconnect technology. In short, there is no lack of challenges and no shortage of stimulating areas of research in this field!

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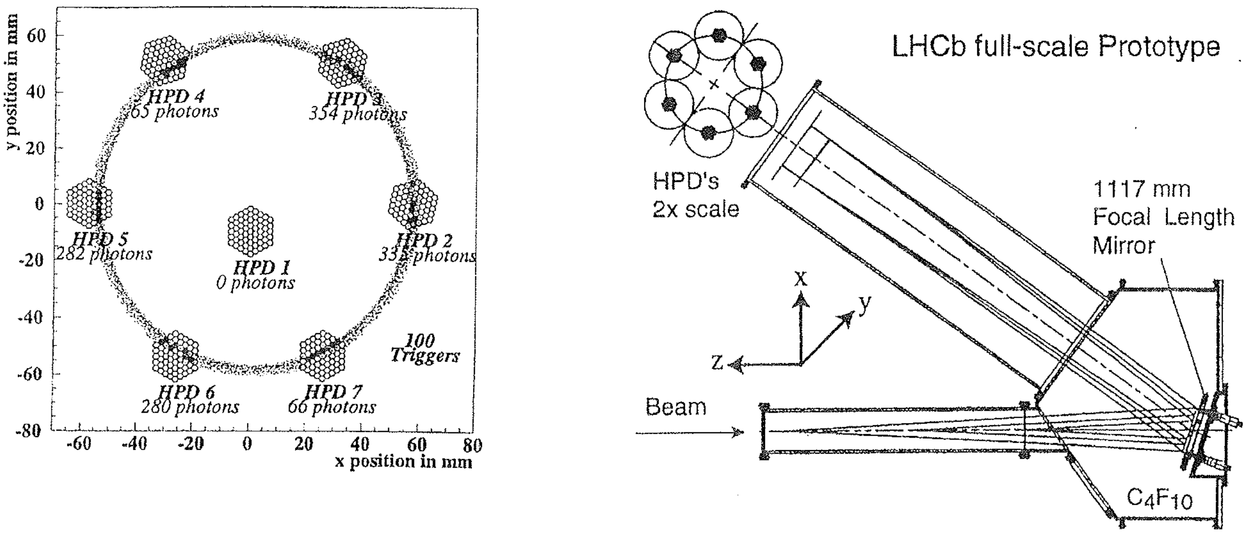
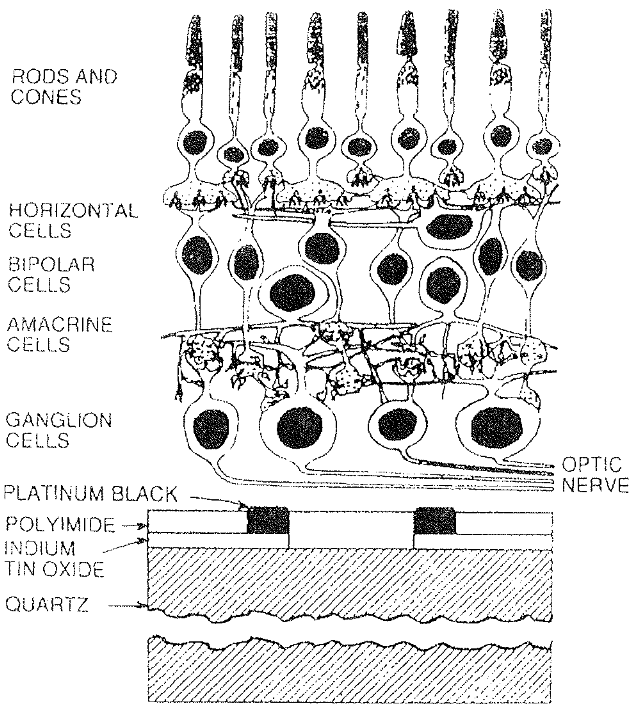



*Fig. 14. Results of tests of an LHCb collaboration prototype ring-imaging Cerenkov detector (RICH2) in a 15.5 GeV/c test beam at the CERN laboratory, illustrating the detection of the Cerenkov photons in an array of silicon pixel detectors.*




A schematic view of the retina placed on top of an electrode array. The vertical dimensions of the electrode array as drawn are not to scale; the correct dimensions are given in the text.

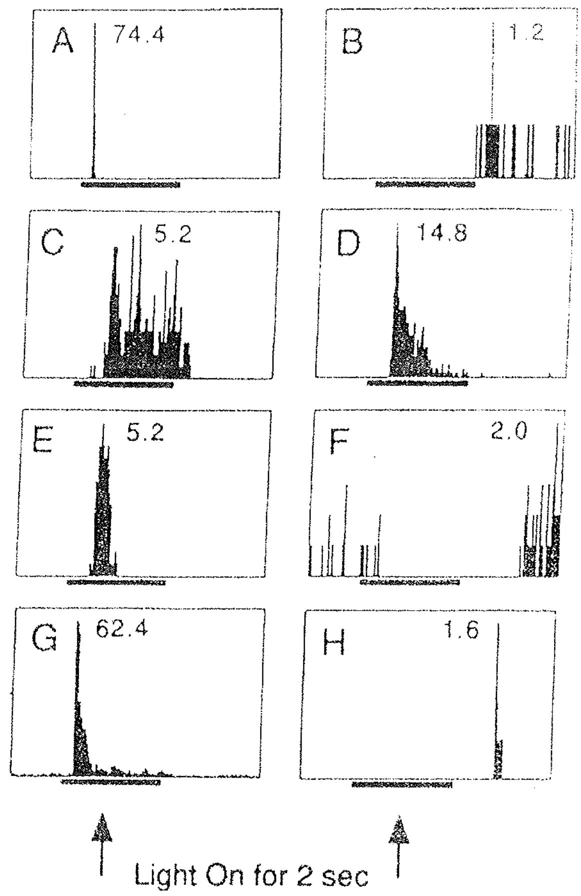



*Fig. 15. Light pattern-induced electrical signals from a salamander´s retinal neurons, detected using an regular array of 61 microelectrodes connected to microelectronics circuits developed originally for high energy physics applications, (cf. Ref. /58/). On the left is a representation of the cross-section of the retina, which is preserved in saline solution while illuminated with a range of light patterns from a computer monitor. The variety of electrical signals induced in the microelectrode array by different species of neurons firing is illustrated in the signals shown on the right. The average "spike rate" is shown for each type of neuron identified by the spatial and time correlations among the 61 microelectrode signals.*

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