Advanced Materials for Radiation Detectors and Sensors:
Wide-Gap Semiconductors and Superconductors

NATO Advanced Research Workshop

Warsaw University of Technology
Warsaw, Poland

September 8-10, 2004

# Programme
# and
# Book of Abstracts

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PIELASZEK RESEARCH
BONIFACEGO 74/94
02-936 WARSZAWA
POLAND

TEL: +(4822)7420281
FAX: +(4822)7420282
E-MAIL: BOOKS@PIELASZEK.COM
E-MAIL: CONFERENCES@SCIENCE24.COM



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# Contents

# Introduction

Our NATO Workshop addresses the new material and design issues for advanced detectors and sensors, with the emphasis on wide-bandgap semiconductors and on superconducting devices, demonstrating their outstanding performance, unsurpassed by any other conventional devices. The Workshop gathers the most experienced specialists from Europe and United States.

The Workshop part devoted to wide-bandgap X-ray and $\gamma$-ray detectors will discuss improvements in the cadmium-based II-VI semiconductor crystals as materials for detection of the radiological nuclear agents and weapons, as well as for precise localization and identification of radioisotopes dispersed in the environment. Lectures presented by the NATO Key Speakers will review fabrication, design, and properties of high performance nuclear radiation detectors based on cadmium telluride CdTe, cadmium-zinc telluride (Cd,Zn)Te, and cadmium-manganese telluride (Cd,Mn)Te crystals. These materials are regarded to be the best choice and should find wide applications in the basic radiation detectors, as they are characterized by high stopping power, excellent transport properties, relatively wide energy gap, as well as mechanical, chemical, and thermodynamical stability.

The Workshop part devoted to superconducting detectors and sensors will focus on their macroscopic quantum nature, ultrafast response, and low-noise cryogenic environment. The superconducting sensors exhibit uniquely high degree of accuracy, stability, and speed; they are radiation and interference resistant and suitable for high-density multiplex integration. The superconducting radiation detectors are the most sensitive devices in their class and their practical applications range from astrophysics and radioastronomy, through nuclear research and non-proliferation, to quantum information technologies. Superconducting quantum interference devices (SQUIDs) are ultrasensitive magnetic sensors and they are being successfully, commercially applied for non-invasive characterization of materials and structures in medical examinations, food safety, airport security systems, forensic investigations, and for testing of semiconductor VLSI microprocessor chips.

## Organizing Committee

- Roman Sobolewski, Prof., University of Rochester, ARW co-director
- Andrzej Mycielski, Prof., Institute of Physics PAS, ARW co-director
- Paul Siffert, Prof., General Secretary of the E-MRS
- Marta Z. Cieplak, Prof., Institute of Physics, PAS
- Gordon B. Donaldson, Prof., University of Strathclyde

# NATO Advanced Research Workshop

## Wednesday, September 8th

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### Opening remarks - Andrzej Mycielski, Roman Sobolewski

**08:50 - 09:00**

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### Session: Technology and characterization of CdTe and (Cd,Zn)Te crystals for radiation detectors. Chairman - Paul Siffert

**09:00 - 10:30**

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### Fundamentals of the CdTe and CdZnTe crystal growth

09:00 - 09:45
invited oral

Robert Triboulet[1)]

*1) CNRS, Laboratoire de Physique des Solides et de Cristallogenese, 1 Place Aristide Briand, Meudon Cedex F 92195, France*

The characteristics of the Cd and Te atoms make the Cd-Te chemical bond of iono-covalent nature with a pretty high ionicity of 0.55 that conditions most of the properties of CdTe and even its growth. As a result of this iono-covalent bond, a sharp liquidus compared to III-Vs, a wide homogeneity range (some $10^{18}$ $cm^{-3}$), a retrograde solidus shape, a low thermal conductivity and pre-transition phenomena are as many severe obstacles having a strong influence on the melt growth of CdTe and making it difficult to obtain large crystals of high quality. That is why just about all the techniques of growth of semiconductor materials have been applied to CdTe!
It has also to be pointed out that CdTe is now replaced, for most and perhaps all the applications it gives rise to, by CZT which possesses very specific properties beside CdTe. At macroscopic scale, the CdTe lattice is strengthened by the incorporation of Zn but at microscopic scale, the very strong repulsive mixing enthalpy in the solid leads to a miscibility gap for temperatures below 428C, as theoretically predicted and experimentally verified both in thin films and bulk crystals. Furthermore, the presence of Zn leads to segregation during Bridgman growth of the alloy which strongly affects the crystal growth, adds a difficulty to the control of stoichiometry during the growth process and leads to the appearance of severe strains in the crystals, at the origin of macro-defects like grain boundaries. Different ways have been used to overcome this segregation: the simultaneous control of both Cd and Zn vapor pressures during the growth process, the use of a replenishing melt and crucible or the use of THM with particular composite source material geometry.
After discussing all these aspects, the most recent achievements in the growth of CdTe and CZT will be presented and discussed.

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09:45 - 10:30
invited oral

## Factors Limiting the Performance of Large-Volume CZT Detectors

**Ralph B. James**[1], **L. Li**[2], **A. E. Bolotnikov**[1], **G. W. Wright**[1], **G. Camarda**[1], **G. Carini**[1], **Z. Zhong**[1], **D. P. Siddons**[1], **B. Barber**[3]

*1) Brookhaven National Laboratory (BNL), Upton, NY 11973, United States*

*2) Yinnel Tech, South Bend, IN 46619, United States*

*3) University of Arizona, Tucson, AZ 85724, United States*

Cadmium zinc telluride (CZT) is one of the most promising materials for production of large-volume gamma-ray spectrometers and imaging arrays operable at room temperature. The performance of CZT devices, the global capacity for growth of detector-grade crystals, and the size of the commercial market have progressed steadily over the past ten years. Because of deficiencies in the quality of the material, high-resolution CZT spectrometers are still limited to relatively small dimensions ($<$ 2-3 $cm^3$), which makes them inefficient at detecting high photon energies and somewhat ineffective for weak radiation signals except in near proximity. The detectors are very attractive for a much broader range of applications; however, increases in their efficiency are needed without sacrificing the ability to spectrally resolve gamma energies. Achieving the goal of low-cost efficient detectors requires progress in the following areas: growth of large uniform single crystals, reductions in carrier trapping, increases in electrical resistivity, and improved device fabrication procedures. Despite the current material constraints, several types of electron-transport-only detectors have been developed: pixel, coplanar-grid, cross-strip, drift-strip, orthogonal coplanar strip, and virtual Frisch-grid, some of which are now addressing important applications. These devices have many similar operational features and common problems limiting their performance. This talk summarizes the material factors limiting performance of CZT detectors and the common constraints on detector designs: bulk and surface leakage currents, surface effects, properties of Schottky contacts, surface interfacial layers, charge sharing and loss in multi-electrode devices, charge transport non-uniformities, and fluctuations in the pulse height for long-drift devices. We also describe new capabilities at Brookhaven for CZT device characterization and recent progress to characterize the material and devices.

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**10:30 - 10:50**

## Coffee break

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**10:50 - 12:20**

## Session: Technology and characterization of CdTe and (Cd,Zn)Te crystals for radiation detectors - continued. Chairman - Paul Siffert

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10:50 - 11:35
invited oral

## (Cd,Zn)Te radiation detectors: crystal growth and technology

**Michael Fiederle**[1]

*1) Albert-Ludwig-Universität Freiburg, Freiburger Materialforschungszentrum, Stefan-Meier-Strasse 21, Freiburg D-79104, Germany*

The interest in CdTe and (Cd,Zn)Te detectors for application in the area of security is huge. The detectors can be operated at room temperature, the detection efficiency is high and the energy resolution is close to cooled germanium detector systems. However, there are still several limitations due to the material properties, particularly the crystal quality and uniformity of CdTe as well as of (Cd,Zn)Te. One reason for these limitations is the formation of defects and compensation mechanism. A compensation model is presented and discussed for doping

with different elements (In, Cl, Sn, Ge) to show the influence of the compensation mechanism on the detector performance. The material properties are presented for (Cd,Zn)Te and CdTe crystals. All the crystals were grown in Freiburg from the melt by the vertical Bridgman method. The materials properties were obtained by Spatial resolved Photoluminescence measurements and Contactless Resistivity Mappings COREMA. It could be shown that it is possible to grow high resistivity material up to $10^{10}$ Ωcm and a mobility-lifetime-product for electrons of $10^{-3}$ $cm^2/V$. The results of impurity analysis using Glow Discharge Mass Spectroscopy and the PICTS data of trapping levels identified a intrinsic deep level in the middle of the band gap. The detector performance will be presented for planar detectors and large volume detectors with a thickness up to 10 mm.

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## Session: II-VI crystals for radiation detector applications. Chairman - Robert Triboulet

**14:00 - 15:30**

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## Is the (Cd,Mn)Te crystal a prospective material for X-ray and $\gamma$-ray detectors?

14:00 - 14:45
invited oral

**Andrzej Mycielski[1)], A. Burger[3)], M. Sowinska[2)], M. Groza[3)], P. Wojnar[1)], A. J. Szadkowski[1)], B. Witkowska[1)], W. Kaliszek[1)], P. Siffert[4)]**

*1) Polish Academy of Sciences, Institute of Physics, al. Lotnikow 32/46, Warszawa 02-668, Poland*

*2) EURORAD C.T.T., 23, Rue du Loess - BP 20, Strasbourg Cedex 2 F-67037, France*

*3) Fisk University, Department of Physics, Materials Science and Applications Group, 1000 17th Ave. N., Nashville, TN 37208-305, United States*

*4) European Materials Research Society - Headquarters, 23, Rue du Loess - BP 20, Strasbourg Cedex 2 F-67037, France*

To answer the title question - the technology and properties of the (Cd,Mn)Te crystals will be discussed as compared with those of the more commonly used (Cd,Zn)Te crystals.
The composition homogeneity of the large single crystals of the ternary compound seems to be easier to achieve in the case of (Cd,Mn)Te because the segregation coefficient of Mn in CdTe is negligible whith respect to that (approx. 1.4) of Zn
Only 15% of MnTe has to be added to CdTe to reach the best for the detector application value of the energy gap (in the range 1.7 - 2.2 eV), while the necessary amount of ZnTe is over 30%! This is because the composition dependence of the CdTe energy gap is for Mn twice as strong as for Zn. Using a smaller amount of the second cation diminishes many alloying-related problems.
Dopant-free as grown (Cd,Mn)Te crystals are of p-type, which is related to the Cd vacancies acting as acceptors. The number of vacancies can be reduced by the post-growth annealing in the Cd vapours and the high ( $10^{10}$ Ωcm ) resistivity, required for good detectors, can be obtained by doping with donors.
The technology of the (Cd,Mn)Te crystals, undoped and compensated in the very large range of concentrations, and Cd-annealing of the samples will be discussed. Characterization of the obtained crystals by the measurements of resistivity, photoluminescence and photoconductivity will be described. The behaviour of the preliminary detectors will be shown.

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14:45 - 15:30
invited oral

## Defect equilibrium, reactions and complex formation in CdTe and (Cd,Zn)Te

**Roman Grill**[1)], **J. Franc**[1)], **E. Belas**[1)], **P. Höschl**[1)], **P. Moravec**[1)]

*1) Charles University, Institute of Physics, Ke Karlovu 5, Prague 2 CZ-121 16, Czech Republic*

Thermodynamic properties of native defects and their interactions with extrinsic defects including self-compensation, defect reactions and complex formation are studied within quasichemical formalism both at the high temperature annealing and at the cooling down to the room temperature (RT). We shall show that the cooling process significantly influences RT electric properties and the proper thermal treatment can be conveniently used for the optimization of electric properties and preparation of detector grade material. Various defect reactions, which proceed during respective cooling regimes, will be discussed and their effect to RT electric properties will be presented. Special attention will be devoted to defect reactions, which change the electric state of input/output species and allow in some cases the conductivity type conversion or the production of the semi-insulating material. Critical review of present defect models in CdTe will be given.

The defect statistics in CdTe is determined by the Fermi energy, cadmium or tellurium chemical potential and in case of doping by chemical potential of the dopant. In equilibrium with ambient vapor the pressure of one component is used to tune the deviation from stoichiometry ($\Delta$). Both neutral and charged defect densities are calculated solving two balance equations - electric neutrality condition, which ensures the total charge equilibrium, and the dopant balance equation, which fixes dopant density. A cooling, which is sufficiently fast, prevents the sample to reach the equilibrium with external atmosphere and $\Delta$ is preserved at the value, which was set by the previous annealing. Nevertheless, the diffusion is sufficiently fast to allow short-range defect transport and reactions within the material. The set of balance equations must be then completed by the Cd (or Te) balance equation, which fixes $\Delta$ and allows the assessment of respective chemical potential.

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**15:30 - 16:00**

## Coffee break

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**16:00 - 18:15**

## Session: II-VI crystals for radiation detector applications - continued. Chairman - Robert Triboulet

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16:00 - 16:45
invited oral

## Growth and properties of semi-insulating CdZnTe for radiation detector applications

**Csaba Szeles**[1)]

*1) eV PRODUCTS, a division of II-VI, Inc., 373 Saxonburg Blvd., Saxonburg, PA 16056, United States*

The high gamma-ray absorption efficiency and optimum band gap (1.57 eV) makes CdZnTe a near ideal material for room-temperature semiconductor detector applications. Continuous progress in the CdZnTe crystal growth and device fabrication technologies in the last ten years allowed the commercialization of this detector technology into a wide array of medical, industrial, scientific, security and safeguards applications. Increasing yields of the state-of-the-art crystal growth and device fabrication technologies continue to improve the availability and affordability of CdZnTe detectors. While premium-grade large-volume CdZnTe single crystals with superior spectroscopic performance are still relatively expensive, small-volume ($< 0.5$ cm$^3$) high-quality CdZnTe detectors can now be mass-produced and are available at

hundredth of a cost than few years ago. Advancement of the CdZnTe crystal growth technology holds the key to both the further performance improvements of CdZnTe detectors in advanced spectroscopic and spectroscopic imaging applications and the further commercialization of this technology to mainstream room-temperature x-ray and gamma-ray detection applications.
The high-pressure electro-dynamic gradient-freeze (HP-EDGF) crystal-growth technology pioneered by eV PRODUCTS improved the availability of premium grade large-volume semi-insulating CdZnTe crystals and significantly improved the manufacturing yields of CdZnTe detectors. In this contribution we review the properties and performance of CdZnTe crystals grown by the HP-EDGF method. We discuss the nature and effects of electrically active microscopic and structural defects on the charge-transport properties and performance of CdZnTe detectors. We also discuss some of the efforts aiming at further improvements of the CdZnTe crystal growth technology.

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## Development of portable CdZnTe spectrometers for remote sensing of signatures from nuclear materials

16:45 - 17:30
invited oral

**Arnold Burger**[1)], **U. N. Roy**[1)], **M. Groza**[1)], **M. Guo**[1)]

*1) Fisk University, Department of Physics, Materials Science and Applications Group, 1000 17th Ave. N., Nashville, TN 37208-305, United States*

Room temperature cadmium zinc telluride (CZT) gamma-ray spectrometers are being developed for a number of years for medical, space and national security applications where high sensitivity, low operating power and compactness are indispensable. The technology has matured now to the point where large volume (several cubic centimeters) and high energy resolution (approximately 1% at 660 eV) gamma photons, are becoming available for their incorporation into portable systems for remote sensing of signatures from nuclear materials. The straightforward approach of utilizing a planar CZT device has been excluded due to the incomplete collection arising from the trapping of holes and causing broadening of spectral lines at energies above 80 keV, to unacceptable levels of performance. Solutions are being pursued by developing devices aimed at processing the signal produced primarily by electrons and practically insensitive to the contribution of holes, and recent progress has been made in two areas, material growth and signal processing. Present materials challenges are in the growth of CZT boules from which large, oriented single crystal pieces can be cut to fabricate such sizable detectors. Since virtually all the detector grade CZT boules consist of several grains, the availability and costs of a large, single crystal section is still high. Co-planar detectors, capacitive Frisch-grid detectors and devices taking advantage of the small pixel effect, are configurations with a range of requirements in crystallinity and defect content and, involve variable degrees of complexity in the fabrication, surface passivation and signal processing. These devices have been demonstrated by several research groups and will be discussed in terms of their sensitivity and availability.

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## Applying advanced solid-state radiation detector technologies for public protection

17:30 - 18:15
invited oral

**Sam S. Hsu**[1)]

*1) DOSITEC, Inc., 7 Ave D, Hopkinton, MA 01748, United States*

Nuclear and radioactive dirty bombs are among the high risks threats from terrorists today. Therefore, it is essential for countries to prepare their Homeland Defense / First Responders and Military. However, there is very little being done for the general public. Here we focus on the techniques for developing low cost, high performance, easy-to-use and easy-to-interpret devices for the general public. Following are examples of some of these devices:

> Miniature "NUKE" for personal nuke safeguard
> Nuke I.D. Card for non-radiation workers
> BEQ Meter for periodically checking food and drink contamination
> Gamma camera for locating hidden radiation sources

All these instruments are based on advanced solid-state radiation detector technologies and

electronics. Details of the unique characteristics of each device will be given during the presentation.

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# Thursday, September 9th

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09:00 - 10:30

## Session: Applications of the II-VI based semiconductor detectors. Chairman - Ralph B. James

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09:00 - 09:45
invited oral

## Security control by an innovative X-ray method

**C. Burggraf**[1), **P. Siffert**[2)

*1) University Louis Pasteur, Strasbourg, France*

*2) European Materials Research Society - Headquarters, 23, Rue du Loess - BP 20, Strasbourg Cedex 2 F-67037, France*

Luggage inspection in airport by controlling the absorption of an X-ray beam are routinely used since several decades. In general, the d.c. current generated in a silicon photodiode coupled to a scintillator measures the absorption of the beam. More sophisticated systems have also appeared, for example based on single photon spectroscopic counting or dual energy arrangements.

In the present presentation, an alternative method is considered, still based on X-rays, but based on inelastic diffusion and single counting mode in advanced CdTe detectors. This method uses the rather large energy spectrum emitted by a X-ray tube, when impinging in a polycrystalline material. In this later, a family of crystalline planes ($h_i$, $k_i$, $l_i$) always finds the photon of a wavelength $\lambda_i$, such that the Bragg relation, expressed by:

$$d(h_i, k_i, l_i) = n\lambda_i / 2\sin\theta_i$$

can be fulfilled. This method is well known by the crystallographer, sometimes called wrongly "Laue Scattering". Here, single crystallinity is no longer necessary; and we can have a series of diffraction rings, without the any displacement of the sample, nore a change in the X-ray emission spectrum. A complete theoretical and analytical description will be given in the lecture.

Experimentally, it becomes possible to establish a library of crystalline powders spectra, specific for each molecular structure and, consequently, determine quite univocally the exact structure of a drug or an explosive. An illustration will be considered for a shoe analysis.

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09:45 - 10:30
invited oral

## Gamma spectroscopy with room temperature semiconductor detectors and scintillation probes operating without PMT

**Małgorzata Sowińska**[1)

*1) EURORAD C.T.T., 23, Rue du Loess - BP 20, Strasbourg Cedex 2 F-67037, France*

In recent years, wide gap semiconductor materials, such as CdTe and CdZnTe made substantial progress, which makes them competitive for high sensitivity gamma-ray detection under small volumes and without any cooling, as needed for homeland security problems. Nowadays, high resistivity large crystals become available and the earlier charge transport problems can be solved either electronically or by specific detector geometry structures. Single charge sensing detectors, either pixelized, coplanar, hemispherical structures allow to minimize the hole trapping problem and considerably improve the energy resolution for sizing of at least 1 $cm^3$ (equivalent to approx. 5 $cm^3$ Germanium).

The imaging systems based on these semiconductors, without the expensive and cumbersome

PMT systems, can be lightweight, hand-held and operated for long periods of time.
In this presentation, focus is given to two important applications in homeland security applications, namely the identification of gamma emitters by high sensitivity spectrometers with different kind of geometries and also to the localization of hidden sources by small portable imagers.

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## Coffee break

**10:30 - 10:50**

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## Session: Applications of the II-VI based semiconductor detectors - continued. Chairman - Ralph B. James

**10:50 - 12:20**

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## Neutron Detection with Cryogenics and Semiconductors

10:50 - 11:35
invited oral

**Zane W. Bell**[1)], **D. A. Carpenter**[2)], **S. S. Cristy**[2)], **V. E. Lamberti**[2)], **A. Burger**[3)], **B. F. Woodfield**[4)], **T. Niedermayr**[5)], **I. Dragos Hau**[5)], **S. E. Labov**[5)], **S. Friedrich**[5)], **K. R. Pohl**[6)], **L. van den Berg**[6)]

*1) Oak Ridge National Laboratory, Nuclear Science and Technology Division, Oak Ridge, TN 37831-601, United States*

*2) Y-12 National Security Complex, United States*

*3) Fisk University, 1000 Seventeenth Avenue North, Nashville, TN 37208-305, United States*

*4) Brigham Young University, Provo, United States*

*5) Lawrence Livermore National Laboratory (LLNL), 7000 East Ave., L-270, Livermore, CA, United States*

*6) Constellation Technology Corporation, Largo, United States*

Advances in materials and methods have enabled the detection of radiation by means today that would have seemed like science fiction a century ago to pioneers in the field. Improvements in technology have resulted, for gamma ray detection, in high-purity germanium operating at 77 K and providing 0.1% energy resolution, more than an order of magnitude improvement over what was (and still is) achievable by scintillators. However, operating below 1 K, cryogengic calorimeters have been used in x-ray astronomy, in the search for dark matter, and more recently in gamma ray spectroscopy, and have achieved 70 eV resolution at 60 keV, an order of magnitude improvement over high-purity germanium. Meanwhile, at the other end of the temperature spectrum, the development of new, wide band-gap semiconductors has sparked research in room temperature gamma detectors and has held out the hope of 1 - 2% resolution and freedom from cryogenics. With such results being reported from the x- and gamma ray world it is natural to examine the possibilities for neutron detection. A cryogenic neutron detection would operate by detecting the heat pulses caused by neutron capture and scattering, while a semiconducting detector would detect the nuclear reaction products from a sensitizer (for example, fission fragments detected in a $^{235}$U-coated Si diode) or from some constituent of the semiconductor. In this paper, we will briefly review the common methods of neutron detection, and discuss the application of cryogenics and semiconductors to the problem. Work on LiF-based calorimeters will be discussed, and on the work by the present authors on the search for, and successful demonstration of a boron-based instrument. Turning to semiconductors, we will discuss CZT, $HgI_2$, and other materials with constituents with high neutron interaction cross sections that can be applied to neutron detection. Results obtained by the authors with $HgI_2$ will be shown.

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11:35 - 12:20
invited oral

## Radiation damage in room temperature detectors

**Anna Cavallini**[1], **A. Castaldini**[1], **B. Fraboni**[1], **L. Polenta**[1], **L. Rigutti**[1]

*1) University of Bologna, Department of Physics, Viale Berti Pichat 6/2, Bologna, Italy*

Radiation damage strongly affects the performance of room temperature detectors. The interaction of ionizing particles often causes an increase in leakage current, a degradation of energy resolution and a shift of the peak position due to the lost charge collection efficiency. The origin of these effects is linked to the presence of electrically active defects that intervene in the charge carrier transport properties. We have carried out a systematic study on the effects of the exposure to electrons, gamma-rays, protons and neutrons of various energies and doses/fluences on detectors based on different materials: $Cd_{0.9}Zn_{0.1}Te$, CdTe:Cl , SiC and GaAs. All the above-cited materials have peculiar characteristics that correspond to pros and cons in different applications, and also have very different fallout on device costs and environmental electronics. This paper addresses the analysis of the modifications induced on each of these materials by different types of radiation and the study is performed from the viewpoint of the microscopic defects that are generated/modified by particle radiation and of the electronic levels associated to them. Such a rather challenging task will be dealt with by studying the charge carrier transport properties using gamma spectroscopy analyses ($^{57}$Co and $^{241}$Am), dark current and capacitance-voltage measurements, as well as junction spectroscopy investigations (DLTS and PICTS). The results obtained by utilizing these tools have to be cross-correlated if we are to disentangle the effects of the various defects. Radiation induced defects will be shown to play a paramount role in the material compensation process, which in turn determines the electric field distribution across the detector. Indeed, the correlation between particular defects and transport properties is sometimes evident while in other cases is far from being satisfied. It is also reported that "large density of specific defects" not always mean "low detector efficiency": in CdZnTe only some defects are really effective as lifetime killer and in SiC a ionising radiation generates a very large amount of defects with no appreciable change in the detector efficiency. That comparison will, hopefully, help better understanding and improvement of devices.

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**14:00 - 15:30**

## Session: Novel superconducting materials and applications. Chairman - Marta Z. Cieplak

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14:00 - 14:45
invited oral

## Cold (and Hot) Wars: a History of Superconductivity from Weissberg Cibulski to the Nobel 2003

**Georges Waysand**[1]

*1) Universities Pierre et Marie Curie - Paris 6 and Denis Diderot - Paris 7, Solid State Physics Group, Tour 23, 2 Place Jussieu, Paris CEDEX 05 F-75251, France*

Far from being a continuous flow from its discovery down to its explanation, the actual history of superconductivity has been affected by numerous turbulences all along the XXth century. This talk will explore the most significant events from the 30's to the 2003 Nobel prize for physics: low-temperature in Kharkov with Shubnikov and Weissberg Cibulski (childhood friend of Arthur Koestler's wife); rebirth of cryophysics in UK mostly by German Jewish physicists, forced to exile by Hitlerism; superfluidity discovered in Moscow, thanks to Stalin, and in Cambridge in spite of him. This chaotic history culminated in two theoretical parallel developments isolated one from each other during the cold: Ginzburg-Landau on one hand, BCS on the other. As a result, superconductivity is not only a fascinating development in physics but also a study case of relationships between physics and society.

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## Single crystals of pure and substituted $MgB_2$: crystal growth and physical properties

14:45 - 15:30
invited oral

Janusz Karpinski[1)], N. Zhigadlo[1)], S. M. Kazakov[1)], J. Jun[1)], E. Müller[1)], M. Angst[1,6)], R. Puzniak[2)], A. Wisniewski[2)], M. Eskildsen[3,7)], R. Gonnelli[4)], K. Rogacki[5)]

*1) Solid State Physics Laboratory ETH, Schafmatstr. 16, Zürich CH-8093, Switzerland*

*2) Polish Academy of Sciences, Institute of Physics, Al. Lotnikow 32/46, Warszawa 02-668, Poland*

*3) University of Notre Dame, Notre Dame, IN 46556, United States*

*4) Politecnico di Torino, Torino 10129, Italy*

*5) Polish Academy of Sciences, Institute of Low Temperature and Structure Research, Wroclaw 50-950, Poland*

*6) Iowa State University of Science and Technology, Ames, IA 50011, United States*

*7) University of Geneva, Geneva 1211, Switzerland*

$MgB_2$ is a two-gap superconductor with several anomalous properties originating from the existence of two separate sheets of the Fermi surface, one quasi 2D ($\sigma$ band) and second quasi 3D ($\pi$ band). This leads to temperature and field dependent anisotropy and high critical temperature of 39K. Prospects of applications of $MgB_2$ depend on a success in increasing the critical parameters such as the upper critical field and critical current. This can be realized via substitutions of B or Mg. Substitutional chemistry is one of the most effective methods to modify the electronic properties of superconductors. Partial replacement of B by C, or Mg by Al in $MgB_2$ single crystals introduces additional electrons which influences superconducting properties, electronic structure and energy gaps. The magnetic properties investigations with torque magnetometer and the transport investigations show twice increase of the upper critical field with carbon substitution. The behavior of two gaps as a function of temperature and field has been studied by the point contact spectroscopy and the scanning tunneling spectroscopy. However, defects introduced by substitutions led to formation of domains, vacancies and inhomogeneities in the structure, which influence the properties as well. Transition electron microscopy and single crystal x-ray investigations show the influence of substitutions on defect formation in the structure.

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## Coffee break

**15:30 - 16:00**

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## Session: Novel superconducting materials and applications - continued. Chairman - Marta Z. Cieplak

**16:00 - 17:30**

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## Nanoscale superconducting devices for sensors and other applications

16:00 - 16:45
invited oral

Mark G. Blamire[1)], C. Bell[1)], G. Burnell[1)]

*1) University of Cambridge, Department of Materials Science and Nanoscience Centre, Pembroke Str., Cambridge CB2 3QZ, United Kingdom*

The methods of superconducting device fabrication by lithography and multilevel pprocessing usually require a number of processing steps with lithographic resolution and alignment adequate for the scale of the device be fabricated. As an alternative, the focused ion beam (FIB) microscope is increasingly being used to actively fabricate devices. A major advantage of using a FIB compared to other beam lithography methods is its flexibility. It allows in-situ, high resolution milling ( 8 nm at a beam current of 1 pA) to a variety of depths, and imaging (6 nm) of the sample. In this paper we describe our development of junction fabrication techniques using the FIB and their application in creating a range of potential sensor devices. The paper will cover both nanoscale SQUID devices and other structures with potential quantum electronics applications.

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## Critical currents and current-phase relation of SFS Josephson junctions

16:45 - 17:30
invited oral

**Valeriy V. Ryazanov**[1)], **V. A. Oboznov**[1)], **V. V. Bolginov**[1)], **A. S. Prokofiev**[1)], **S. M. Frolov**[2)], **D. J. Van Harlingen**[2)]

*1) Institute of Solid State Physics RAS, Laboratory of Superconductivity, Institutskaja,2, Chernogolovka 142432, Russian Federation*

*2) University of Illinois at Urbana-Champaign, Department of Physics, Urbana, IL 61801, United States*

Superconductor - ferromagnet - superconductor (SFS) $\pi$-junctions [1] were investigated experimentally in detail. The transitions to $\pi$-state and back to the conventional 0-state were found to result from temperature decrease or ferromagnetic interlayer thickness increase. Thickness dependence of the critical current was studied and nonmonotonic behavior related to the spatial oscillations of the induced superconducting order parameter in a ferromagnet was observed. Thickness dependences of the SFS-junctions (Nb-$Cu_{1-x}Ni_x$-Nb) were measured for several contents of Cu/Ni-alloy. The following results were obtained:
i) the larger magnetic content of F-layer the smaller the period of the order parameter spatial oscillations;
ii) there is quite good quantitative agreement between values of the oscillation period extracted from the SF-bilayer and SFS junction measurements for ferromagnetic layers prepared by the same rf-sputtering method with using the same target;
iii) value of the imaginary part of the coherence length in the ferromagnetic Cu/Ni is found to be much larger than the order parameter decay length due to existence extra mechanisms of the order parameter decay in Cu/Ni alloy, mainly the strong spin-flip scattering on nickel-rich clusters nucleated in the alloy.
We present also measurements of the current-phase relation (CPR) of SFS Josephson junctions as a function of temperature. The CPR is determined by incorporating the junction in an superconducting loop coupled to a dc SQUID, allowing measurement of the junction phase difference. We find that the critical current is negative for T smaller than temperature of 0-$\pi$-transition, indicating that the junction is a $\pi$-Josephson junction.
[1] V.V. Ryazanov, V.A. Oboznov, A.Yu. Rusanov, A.V. Veretennikov, A.A. Golubov, and J. Aarts. Phys. Rev. Letters 86, 2427 (2001).

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# Friday, September 10th

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## Session: Superconducting Radiation Detectors. Chairman - Roman Sobolewski

**09:00 - 10:30**

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## Semiconducting single-photon detectors: the state-of-the-art

09:00 - 09:45
invited oral

Ivan Prochazka[1)]

*1) Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering, Department of Physical Electronics, Brehova str. 7, Prague 1 115 19, Czech Republic*

Solid state single photon detectors are getting more and more attention in various areas of applied physics: optical sensors, communication, quantum cryptography, optical ranging and Lidar, time resolved spectroscopy, opaque media imaging and ballistic photon identification. We are reporting on results in research and development in the field of solid state single photon detectors at the Czech Technical University in Prague during the last 20 years. The main design objectives are: semiconducting detector, sensitive area diameters exceeding 50 micrometres, active quenching and gating electronic circuit, high timing resolution and rugged design. Avalanche photodiodes specifically designed for Single Photon counting devices have been developed on the basis of various semiconductor materials: Si, Ge, GaP, GaAs and InGaAs. All the semiconductor detectors operate at a room temperature or at thermoelectrically achievable temperatures except of the germanium based detector, which requires liquid nitrogen cooling. Electronic circuits for these detectors biasing, quenching and control have been developed and optimised for different applications. The sensitivity of solid state photon counters spans from 0.1 nanometre X-ray up to 1800 nanometres in the near infrared region. Timing resolution of solid state photon counters as high as 50 picoseconds full width at a half maximum has been achieved when detecting single photon signals. Circuits permitting operation of solid state photon counters in both single and multiple photon signal regimes have been developed and applied. The compact and rugged design, radiation resistance, and low operating voltage are attractive features of solid state photon counters in various applications including the space projects. The recent results are presented together with the detailed review.

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## Ultrafast Superconducting Single-Photon Detectors for Near-Infrared-Wavelength Quantum Communications

09:45 - 10:30
invited oral

Gregory N. Gol'tsman[1)], W. Slysz[2)], A. Pearlman[3)], A. Verevkin[3)], R. Sobolewski[3)]

*1) Moscow State Pedagogical University, Department of Physics, M. Pirogovskaya, 29, Moscow 119435, Russian Federation*

*2) Institute of Electron Technology (ITE), Al. Lotników 32/46, Warszawa 02-668, Poland*

*3) University of Rochester, Department of Electrical and Computer Engineering, Computer Studies Bldg., CSB410, P.O. Box 270231, Rochester, NY 14627-0231, United States*

We present our progress on the research and development of niobium-nitride, superconducting single-photon detectors (SSPDs) for ultrafast counting of near-infrared photons for secure quantum communications. The SSPDs operate in the quantum detection mode, based on photon-induced hotspot formation and subsequent development of a transient resistive barrier across an ultrathin and submicron-width superconducting stripe. The devices are fabricated from 4-nm-thick NbN films and kept at cryogenic (liquid helium) temperatures. The detector experimental quantum efficiency in the photon-counting mode reaches above 40% in the visible range of radiation and up to 30% at the 1.3 to 1.55 $\mu$m infrared range. The dark counts are below 0.01 per second. The measured real-time counting rate is above 2 GHz and is limited by our readout electronics. The SSPD jitter is below 18 ps, and the best-measured value of the noise-equivalent power (NEP) is 5 x $10^{-21}$ W/Hz$^{1/2}$ at 1.3 $\mu$m. In terms of the photon-counting efficiency and speed, our NbN SSPDs significantly outperform semiconductor avalanche photodiodes and photomultipliers at the 1.3 to 1.55 $\mu$m infrared range.

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## Coffee break

**10:30 - 10:50**

10:50 - 12:20

## Session: Superconducting Radiation Detectors - continued. Chairman - Roman Sobolewski

10:50 - 11:35
invited oral

### Superconducting transition edge sensors for photon-number resolving detection in quantum information applications

**Sae Woo Nam**[1)]

*1) National Institute for Standards and Technology, Quantum Devices Group, M.S. 817.03 325 Broadway, Boulder, CO 80305-3328, United States*

New quantum-based communication and measurement systems that use single and correlated photons is an active area of research. The current tools to calibrate the components in these systems are inadequate for these emerging applications. For accurate calibrations, a detector capable of determining the number of photons in a single pulse of light is needed. We have demonstrated a new detector that is capable of determining the photon number state in quantum interferometry. This single photon counting device is based on the superconducting transition-edge sensor (TES) technology currently being developed for photon-counting from gamma rays down into the near-infrared. By exploiting the sharp superconducting-to-normal resistive transition of tungsten at 100mK, these TES single photon counters give an output current pulse that is proportional to the cumulative energy in an absorption event. This proportional pulse-height enables the determination of the energy absorbed by the TES and the direct conversion of sensor pulse-height into photon number. I will discuss our results of using this new type of detector in quantum information applications and our progress towards developing detectors with quantum efficiencies approaching 100%.

11:35 - 12:20
invited oral

### Ultra-high resolution Gamma spectrometry for nuclear attribution

**Stephan Friedrich**[1)]

*1) Lawrence Livermore National Laboratory, Advanced Detector Group, 7000 East Ave., L-270, Livermore, CA 94550, United States*

Cryogenic Gamma-ray spectrometers operated at temperatures around 0.1 K offer an order of magnitude higher energy resolution than conventional Ge detectors. This greatly increases the precision of non-destructive isotope ratio measurements in complicated nuclear mixtures. We are developing Gamma-ray spectrometers based on bulk Sn absorber crystals attached to superconducting Mo/Cu thermistors. The Mo/Cu thermistor is operated at the superconducting-to-normal transition where its resistance changes sensitively with temperature. Gamma-ray capture increases the temperature of the Sn absorber in proportion to the Gamma energy, and this increase is recorded as a change in the resistance of the superconducting Mo/Cu sensor. For user-friendly operation, we have also developed a two-stage adiabatic demagnetization refrigerator that allows detector operation at 0.1 K at the end of a cold finger within 2 cm of a room temperature radioactive sample. Our spectrometer has achieved an energy resolution between 60 and 90 eV for Gamma energies up to 100 keV. For increased efficiency and count rate capabilities, we are currently developing detector arrays and the multiplexing technology required to read out many independent channels with a single SQUID preamplifier. We have already shown that two detector pixels can be multiplexed without loss in energy resolution. We will discuss the performance of the instrument in the context of precision analysis of radioactive samples for nuclear attribution.

# Session: Ultrasensitive SQUID magnetic sensors for non-invasive material and structure characterization. Chairman - Gordon B. Donaldson

**14:00 - 15:30**

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## SQUIDs and their applications

14:00 - 14:45
invited oral


Gordon B. Donaldson[1)]

*1) University of Strathclyde, Department of Physics and Applied Physics, John Anderson Building, 107 Rottenrow, Glasgow, Scotland, G4 0NG, United Kingdom*



SQUIDs (Superconducting Quantum Interference Devices) are the most sensitive electromagnetic detectors available, and have been used in many modes as detectors of weak magnetic sources. This talk will discuss the science underlying the operation of SQUIDs and as an introduction to the more specialist talks that follow, will introduce some of their 'routine' applications, such as their use in adult and fetal cardiography and in precision metrology. Finally, noting that the ultimate sensitivity of these devices is 'quantum limited', and set only by the Heisenberg Uncertainty Principle, it will come as no surprise that they have been employed in some very exotic experimental situations. The latest of these involves their deployment in the recently launched Gravity Probe B satellite which is to verify a previously untested prediction of the General Theory of Relativity; In this project, which is to last 1 year, SQUIDs will detect the gyroscopic precession of spinning balls with an angular precision corresponding to that subtended by a human hair at a distance of 20km.


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## SQUID Microscopy and Nondestructive Evaluation

14:45 - 15:30
invited oral


Michael Mueck[1)]

*1) University of Giessen, Institute of Applied Physics, Heinrich-Buff-Ring 16, Giessen 35392, Germany*



SQUIDs (Superconducting Quantum Interference Devices) are magnetic field sensors with unsurpassed sensitivity. They are amazingly versatile, being able to measure all physical quantities which can be converted to magnetic flux. They are routinely fabricated in thin film technology from two classes of superconducting materials: high-temperature superconductors (HTS) which are usually cooled to 77 K, and low-temperature superconductors (LTS), which have to be cooled to 4.2 K.
SQUIDs have many applications, two of which shall be discussed in this talk. In SQUID microscopy, a SQUID scans a sample, which preferrably is at room temperature, and measures the two-dimensional magnetic field distribution at its surface. In order to achieve a relatively high spatial resolution, the stand-off distance between the sample and the SQUID is made as small as possible. For SQUIDs made from high-temperature superconductors this spacing can be as low as 0.01 mm, whereas for low-temperature superconductors, spacings of the order of 0.05 mm have been realized.
SQUIDs show also promising results in the field of nondestructive testing of various materials. For example, ferromagnetic impurities in stainless steel formed by aging processes in the material can be detected with high probability, and cracks in conducting materials, for example aircraft parts, can be located using eddy current methods. Especially for the case of thick, highly conductive, or ferromagnetic materials, as well as sintered materials, it can be shown that a SQUID based NDE system exhibits a much higher sensitivity compared to conventional eddy current NDE and ultrasonic testing.


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## Coffee break

**15:30 - 16:00**

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16:00 - 17:30

## Session: Ultrasensitive SQUID magnetic sensors for non-invasive material and structure characterization - continued. Chairman - Gordon B. Donaldson

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16:00 - 16:45
invited oral

## SQUID detection of flaws in CFRP aircraft components

**Adele Ruosi**[1)]

*1) University of Naples "Federico II", Department of Physics, Piazzale Tecchio, 80, Napoli I-80125, Italy*

Monitoring of structural integrity is an essential issue in enhancing affordability as well safety of modern aircraft and spacecraft structures. High strength and stiffness to weight ratios, which facilitate high load-carrying capacity, are making fiber reinforced composites an attractive alternative construction material for primary aircraft components like flaps, vertical and horizontal stabilizers, wings, tails and fuselage skins. However, due to the brittle epoxy matrix in which the carbon or graphite fibres are embedded, the laminates are susceptible to internal damage caused by impact during their loading use. Damage can be caused by dropping a tool during maintenance, hailstones, bird strikes, stones, and so on. This may lead to delamination, sub-surface matrix cracking, fiber/matrix debonding and fiber fracture. Due to stress and strain, their effects propagate during use altering the strength or the stiffness of the component. At low energy impact, the damage is not always visible on the hit surface but affects internally the sample and has the most effectiveness on the opposite surface. This makes the defect detection from the impacted surface, often the only accessible for investigation, a challenging task. For an early and accurate detection of these defects, especially the ones related to low-velocity impact, probes with extremely high magnetic field sensitivity are needed. The high sensitivity, on a wide frequency range offered by superconducting quantum interference device (SQUID) magnetometers, make them a powerful probe for eddy-current inspection of both metallic and composite material where other nondestructive techniques fail. We will present eddy-current nondestructive testing which use high-$T_c$ SQUIDs, with emphasis on extremely lightweight graphite/epoxy composites damaged by low-velocity impact.

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16:45 - 17:30
invited oral

## SQUID Technology for Geophysical Exploration

**Hans-Georg Meyer**[1)], **R. Stolz**[1)], **A. Chwala**[1)], **V. Schultze**[1)]

*1) Institute for Physical High Technology (IPHT), Albert-Einstein-Strasse 9, Jena D-07745, Germany*

Magnetic measurements are widely used for geophysical surveys. The fields of applications are ranging from mineral exploration, environmental and military monitoring to archaeometry. During the past few years several SQUID systems for geomagnetic measurements have been developed and successfully tested. Compared to conventional systems their outstanding performance was demonstrated. The latest of such systems are mainly based on LTS SQUIDs and shall be summarized here.

Ground-based Transient Electromagnetics is a powerful active method for a detailed investigation of orebodies. The SQUID vector magnetometer designed for that particular application case shows a 100 times better time resolution or a 10 times deeper detection range in comparison to the current induction coil or fluxgate systems.

Airborne geophysics is extremely interesting in prospecting for different applications, since they allow to cover large areas with sufficiently high spatial resolution in short time periods. Geomagnetic measurements detect basically anomalies of the Earths magnetic field.

The recently developed planar LTS SQUID gradiometers with a base length of 4 cm show an intrinsic balance of about $10^4$ and a gradient field resolution better than 100 fT/(mHz$^{1/2}$) down to 0.1 Hz. By means of the airborne SQUID system the complete gradient tensor of the

Earths magnetic field was measured with superior accuracy never reached so far.

Archaeometry with magnetic field sensors needs high spatial resolution down to the range of 10 cm. To cover reasonably large areas there is a need for high sensitive gradiometers with a high bandwidth, allowing a fast scanning speed directly above the soil. For this purpose a portable LTS SQUID gradiometer is under development. First archaeometric field experiments show very promising results.

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## DISCUSSION on future detector and sensor applications.

**17:30 - 18:00**

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## CLOSING remarks - Andrzej Mycielski, Roman Sobolewski

**18:00 - 18:10**

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