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SESSION 5 PHOTOELECTRIC PHENOMENA IN PHOTODETECTORS AND PHOTOSENSITIVE STRUCTURES

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Introduction

Photoelectronics today: On materials of the XIX International Scientific and Engineering Conference on Photoelectronics and Night Vision Devices[1]

Photoelectronics and night vision device mainstream developments were analyzed in the XIX International Scientific and Engineering Conference on Photoelectronics and Night Vision Devices. The most challenging reports were examined, on thermal vision, focal plane arrays, FPA information systems and device cooling systems, electron-optical system engineering topics, photoelectronics materials science including organic, photoelectronics physical phenomena and metrology, etc.

The conference was held in Moscow May 23 through 26, 2006. Dedicated to the Orion RD&P Center 60th anniversary, it included an exhibition of Russian manufacturers' optoelectronic devices.

The conference and the exhibition were organized by the State Research Center of Russian Federation Orion RD&P Center. The conference was supported by the Ministry of Education and Science of the Russian Federation, Russian Federal Agency of Industry, Federal Agency of Science and Innovations, the Russian Academy of Science, the Moscow Government, and the SPIE Russia Chapter.

Conference topics were:

- semiconductor photodetectors and focal plane arrays (photodetection and advanced materials physical research; technologies including electronic and ionic-plasma ones; cooling systems and signal processing methods);
- thermal detectors and focal plane arrays (physical research; technology; cooling systems and signal data processing systems);
- night vision devices (image intensifiers and thermal imagers ones);
- photodetector-oriented microelectronics;
- new trends and recent achievements in the field of IR-photoelectronics and night vision devices.

Approximately 300 reports from about 100 institutes of 10 countries were submitted to the conference. Those were Azerbaijan, Belarus, France, Israel, Poland, the Russian Federation, Turkey, Uzbekistan, and Ukraine. Korean, Lithuanian, and Japanese representatives also took part in the proceedings of the conference.

The reports' research area extends far beyond the strict subject scope of the conference. Besides photoelectronics and night vision devices, the issues concerned in the reports refer to optical devices and their technology,

[1] Whereas some of the submitted reports will not be published in the conference proceedings, the editors considered it necessary and possible to make their detailed overview in the preamble.

photoresponsive material and optoelectronic device technology, and even to innovation methods in photo- and optoelectronic device development and production.

Several mainstreams can be singled out among those considered at the conference[1]:

- Thermal imaging, including thermal imaging devices, focal plane array and submatrix photodetectors for spectral ranges 3–5 and 8–12 μm
- Optoelectronic device cooling systems
- Photoelectronics materials and device structures technology
- ROIS microelectronics
- Microbolometers
- *p-i-n* photodiodes
- Photoelectric phenomena in semiconductors and semiconductor structures
- Image intensifiers
- Night vision devices
- Organic materials in photoelectronics
- Optical devices
- Items of advanced electro-optical devices metrology
- Innovation methods in photoelectronics.

The thermal imaging theme was represented the most extensively. Alongside device reports such as "Thermal imaging camera with the linear 4×288 FPA working in a TDI mode," R. M. Aleev, A. V. Busarev, V. V. Egorova, et al. (*Joint-Stock Company NPF Optooil, Orion RD&P Center*); and "Thermal Imager with linear detector ideology, achievements, results," E. A. Tereshin, P. V. Zhuravlev (*Institute of Applied Microelectronics of RAS*); and others which expounded methods, design, and characteristics of devices under development, there were reports of great interest on photodetectors for thermal imaging devices.

Those were "Photodetector units for second generation thermal imaging systems in Orion," I. D. Burlakov, E.V. Degtyarov, V. P. Ponomarenko, A. M. Filachev (*Orion RD&P Center, SRTI of Defense Ministry*); "HgCdTe large staring arrays at SOFRADIR," Ph. Tribolet, G. Destefanis (*SOFRADIR, France, LETI/CEA, France*); "256×256 LWIR MCT FPA integrated with microcryogenic system," K. O. Boltar, I. D. Burlakov, N. I. Yakovleva, et al. (*Orion RD&P Center*); "Focal plane array of a format 256×256 on basis InSb with fast response and broad functional capabilities," V. F. Chishko, I. L. Kasatkin, A. I. Dirochka, et al. (*Orion RD&P Center, RTK IMPEX*); "Photosensitive device based on MIS-photodiode array on InAs for pulsed optical data registration," I. I. Lee, V. M. Bazovkin, N. A. Valisheva, et al. (*Institute of Semiconductor Physics of RAS*); "The new generation of cooled multi-element photodetector devices based on Pb chalcogenides," G. A. Arakelov, V. D. Bochkov, B. N. Drazhnikov, et al. (*Orion RD&P Center*); "Mono- and bispectral focal plane arrays based on multiple quantum well structures," A. A. Kazakov, V. B. Kulikov, D. V. Borodin, et al. (*FSUE M.F. Stelmakh RDI Polyus*); "Infrared photodetectors based on HgCdTe/CdZnTe/GaAs heterostructures with graded band-gap layer grown by MBE," V. S. Varavin, V. V. Vasiliev, S. A. Dvoretsky, et al. (*Institute of Semiconductor Physics of RAS*) and others.

The papers describe Russian and French researchers' and designers' results in the field of second generation focal plane array photodetectors for primary spectral ranges 1-3, 3-5, and 8-12 μm on the basis of Pb chalcogenides (PbS, PbSe), indium antimonide and arsenide (InAs, InSb), cadmium-hydrargyrum telluride solid solutions ($Cd_xHg_{1-x}Te$), and quantum-well structures.

HgCdTe arrays were presented for the range 3-5 μm of formats up to 640×512 and 1280v1024 elements, as were 288×384 HgCdTe staring focal plane arrays for the range of 8-12 μm that cover a large spectral wavelength range.

Photoelectric and performance specification was analyzed concerning 2×256, 4×288, 256×256, 384×286, 768×576 (CdHgTe), 256×256 (InSb), 2×128 (PbS, PbSe) photodetectors with photoresponse cooled preprocessing circuit design.

Principal application fields were suggested for focal plane array photodetectors in optoelectronic different-purpose hardware. Finally, there were defined IR-photodetectors development trends.

In the line of cooling systems one should note the following papers: "Current state and prospects of thermoelectricity application in optoelectronics," L. I. Anatychuk, V. V. Razinkov (*Institute of Thermoelectricity, Ukraine*); "Aural stealth of portable cryogenically cooled infrared imagers," A. Veprik, H. Vilenchik, R. Broyde, N. Pundak (*RICOR, Israel*); "Thales cryogenics IDDCA coolers," Jean-Yves Martin, Jean-Marc Cauquil (*Thales Cryogenics, France*); and "The development results of modular microcryogenic systems based on the split-Stirling for cryostatting of the first and second generation photodetective assembly," M. V. Lipin, A. V. Gromov (*STC Cryogenic Technique Ltd.*).

Stirling thermodynamic cycle microcryogenic systems (MCS) were considered. Several alternate MCSs were suggested. The designed MCS allows photodetector photosensitive cell thermostating at temperature level (75 ÷80) K under cooling load from 0,3 to 2,0 W. Results were adduced of MCS survey and tests which were carried out under different conditions, with special attention given to acoustic noise reduction.

The immediate prospects of MCS design development as well as its reliability and technical capability enhancement are shown.

The photodetectors convenient for combining with thermoelectric cooling (TEC) and their appropriate cooling temperature ranges were analyzed. Represented data about computer-aided design achievement included both photoelectronics device-oriented TEC and TEC optoelectronic systems at large. Features of TEC processing technique for optoelectronic systems were considered. The papers give an account of improvement trends concerning materials thermoelectric quality, antidiffusion layers, mechanical durability and lifetime.

A most complete presentation was given to technological problems of photoelectronics materials and instrumental structure production in the following papers: "Heteroepitaxial structures HgCdTe for infrared detectors," S. A. Alfimov, A. P. Antsiferov, Yu. G. Sidorov, et al. (*Institute of Semiconductor Physics of RAS*); "Heteroepitaxial MCT LPE structures and multi-element photodevices on their base," L. A. Denisov, A. I. Belogorokhov, N. A. Smirnova, et al. (*FSUE Institute of Rare Metals, Joint-Stock Company Moscow Factory Sapfir*); and "Use of ion source with cool cathode for the decision of technological microphotoelectronics tasks," A. N. Kozlov, A. I. Zaitsev, A. E. Danilovsky, et al. (*Orion RD&P Center*).

Production of MCT LPE heteroepitaxial layers on different substrates was described, along with their application in the field of physic-chemical processes of growth, deliberate doping, defect formation mechanisms in order to create material manufacturing science for third generation infrared photodetectors.

FSUE Institute of Rare Metals (RF) has elaborated the technology and opened up pilot production of indium-doped and undoped MCT *n*-type LPE-epitaxial layers (EL) on cadmium-zinc-tellurium substrates. Received EL characteristics meet the demands made for photoresponsive materials under multi-element photodetector commercial production.

It is suggested that ion sources with cool cathode should be wider used in photosensitive cell technology. In comparison with plasma process technology, ion source process allows independent control of beam energy, ion current density, beam direction, and residual pressure in the camera. Ion sources can operate under low residual pressure and therefore can be appropriate for pure admixture-free processes.

Possessing considerable control flexibility, ion beam systems can be used in multiple task solutions such as substrate and material cleaning; ion-beam, reactive and ion-chemical etching; sputter deposition; reactive sputter deposition; ion assistance at alternative methods of filming; diamond-like layer coating; and modification of material properties or thin films surface morphology modification.

Many reports were dedicated to the issue of development of photoresponse reading and processing microelectronics. Basic among them were those presented by F. F. Sizov, et al. (*V.Ye. Lashkaryov Institute of Semiconductor Physics of NAS, Ukraine*), V. V. Minaev, et al. (*JSC "Angstrem"*), etc.

F. F. Sizov presented comparative analysis of 4×288 different design and technology readouts. All had a direct injection input circuit with incorporated elements, allowing testing without photodiodes, and TDI registers with three delay elements between neighbor inputs. Two-phase and four-phase CCD readouts with different channel types (surface, buried, and semi-buried) contain 10-bit TDI registers a channel, 18-channel multiplexing to 16 outputs.

The basic characteristics were presented: charge handling capacity, transfer characteristics, output nonlinearity characteristics, bias dispersion, etc. Used for data multiplexing, CCD technology results in crosstalk increase due to the presence of rather considerable transfer inefficiency at cryogenic temperatures.

The comparative analysis showed that the readouts differ mainly in number of outputs, external service, but have similar basic parameters.

Scientific Production Enterprise Pulsar, Joint-Stock Company RTK Impex, and Orion RD&P Center have developed a CMOS microcircuit family of signal readout from linear, submatrix and matrix array cameras based on InSb, PbS, PbSe, AlGaAs/GaAs, CdHgTe etc.

Hardware and software equipment for CMOS VLSIC monitoring, diagnostics and production control CMOS have been developed.

Studies on *p-i-n* photodiodes were extensively presented by conference participants from Belarus, Russia, and Turkey.

In a paper by Yu. P. Yakovlev (*Ioffe Physical-Technical Institute of RAS*), the latest achievements are reported in development of LPE- and MOCVD-technology produced *p-i-n* photodiodes based on GaInAsSb/AlGaAsSb and InAsSbP/InAs.

Results of high-speed and high-efficiency GaSb/GaInAsSb/GaAlAsSb photodiodes were considered for the spectral range 1.5–2.5 μm. A wide range of such photodiodes with an active diameter 0.075–2.8 mm has been developed. Their distinctive features are high monochromatic current sensitivity at the spectrum maximum, fast response time — photodiodes with the active diameter 0.075 mm have a bandwidth up to 1.5–2.0 GHz, quick response time (100-300 ps), and low reverse dark current density. Photodiode detectivity at the maximum spectral sensitivity was as high as $(5\text{-}8)10^{10}$ cm W^{-1} $Hz^{1/2}$.

Basic parameters of fast high-efficiency InAs/InAsSbP photodiodes grown with MOVPE method with InAsSbP wide-gap layer for the spectral range 2.0–3.6 μm were described.

Many reports were dedicated to the study of photoelectric phenomena in semiconductors and semiconductor structures. It is necessary to distinguish the paper offered by the "father" of injection photodiodes, V. I. Stafeev (*Orion RD&P Center*), titled "Injection photodiodes." A new class of semiconductor photodetectors (injection photodiodes [IPD]) with internal amplification and high-photosensitivity in the field of intrinsic, extrinsic, far infrared, and submillimeter emission was analyzed.

At high-injection levels no equilibrium electrons and holes concentrations are equal and far exceed the equilibrium concentrations. They determine a base conductivity, when its width is several times more than minority carrier diffusion length. Radiation increases the carrier concentration and reduces the base resistance and its voltage drop. That leads to *p-n* junction voltage rise and increases carrier injection to the base, and therefore additionally reduces its resistance, increases injection, etc. Positive feedback provides the primary photocurrent injection amplification.

The impurity spectrum area irradiation changes impurity levels filling, which leads to not only no equilibrium carrier concentration change, but also to their redistribution and base conductivity.

Irradiation absorption by free carriers changes their energy and mobility. Photosensitivity increases with wavelength growth up to submillimeter spectrum range. These very effects provide basic and additional parametric photocurrent amplification in IPD.

The injection amplification mechanism provides approximately equal amplification of both photosignal and noise, so IPD detectivity is not less than the analogous photodetector one. The amplification coefficient can be up to 10^3-10^6.

At low forward currents the photosensitivity in the intrinsic absorption area is much more than in the impurity absorption area. However, at high currents the impurity photosensitivity can exceed the intrinsic one. In contrast to ordinary photodiodes, high-photosensitivity can be observed at radiation coming from the *p-n* junction opposite side. Impurities doped Ge, Si, GaAs and narrowband semiconductors are used for IR photodetectors.

GaP, GaP_xAs_{1-x} and GaAs, ZnS chemical solutions, and other wideband semiconductors are used for the ultraviolet band. Their photoresponsivity is 200-900 nm in spectrum range. GaAs doped Cr photodiodes and IPD on the basis of GaAlAs–GaAs Heterojunctions have the best performance.

The main IPD advantages are their manufacturability, increased time stability, and reliability. As far as they operate in the forward direction and *p-n*-junction task consists only in minority carrier injection in the base area.

In the study by V.I. Shashkin et al. (*Institute of Physics of Microstructures of RAS*) "IR photoconductivity in InGaAs/GaAs multilayer heterostructures with quantum dots," application prospects are discussed concerning semiconductor heterostructures with quantum dots (QD) as a new material for IR photodetectors.

QD energy spectrum discreteness leads to suppression of the phonon photocarrier relaxation mechanism, their increased lifetime, and dark currents reduction. That allows reckoning on the creation of uncooled photodetectors. In the paper, the current state of research in this field is analyzed. It is mentioned that the QD IR photodetectors implemented sensitivity is still inferior to other existing photodetectors, while optimum operating temperature is about 100 K. Principal problems are associated with low IR-irradiation absorption coefficient and dark injection currents. Survey mainstreams are considered, cherishing hopes for photodetector parameters improvement. Among them there are QD structures engineering for dark current suppression by insertion of additional barrier and tunnel-transparent layers, employment of dot-in-well growth engineering, QD layer-based superlattice structures.

The results of IR photoconductivity in InGaAs/GaAs QD heterostructures are shown. Overgrown QD characteristic dimensions and shape have been studied with transmission electron microscopy. QD array energy levels have been determined by photoluminescence. Under normal incidence, there were several lines in the infrared range (3, 5, and 14 μm) in lateral and vertical photoconductivity spectra. Depending on growth conditions, structures demonstrated one to three spectral lines. A new mechanism for the lateral IR photoconductivity in the structures with two-dimensional (2D) channels near QDs was introduced. The mechanism is concerned with electron mobility alteration in the 2D channel due to Coulomb scattering lowering on charged QDs under their photoexitation and charge neutralization.

In the papers by V. F. Chishko, et al. (*Orion RD&P Center*) and A. E. Klimov, et al. (*Institute of Semiconductor Physics of RAS*), problems of PbSnTe-based photodetectors development are described and indium-doped material photosensitivity mechanisms were revealed.

Several interesting reports on ultraviolet photodetectors study are presented by UralAlmazInvest Co.Ltd. in collaboration with other enterprises.

Orion RD&P Center, CRI Cyclone JSC (RF) and Integral and JSC Peleng (Belorus) presented reports dedicated to microbolometrix matrix development and employment in thermal imaging devices. The reports described technology of production of vanadium oxide films with increased temperature resistance coefficient (TRC) value. Vanadium oxide films are produced by vanadium target magnetron sputtering in argon-oxygen gas mixture and possess TRC value of 1,5–1,8%/°C. Exposure to supplementary annealing in oxygen or oxygen-hydrogen ambient at different temperature and time modes changed TRC value to 5 –6%/ °C.

Silicon nitride film is a fundamental constructional material of microbolometric photodetectors weak link structures, so considerable attention was paid to both development of formation process and research on the properties of low intrinsic stress silicon nitride films. Residual stress in such films causes its deformation and, therefore, changes Fabry-Perot cavity size.

The laboratory of semiconductors in the Institute of Solid State and Semiconductor Physics, National Academy of Sciences of Belarus, succeeded in formation of $Ba_xSr_{1-x}TiO_3$ thin ferroelectric films by a pulsed laser deposition method.

It is necessary to emphasize two reports among dedicated to image intensifiers (II): M. A. Monastyrsky, et al. (*Institute of General Physics of RAS, Orion RD&P Center*), "Computer simulation of image intensifiers and photoelectron guns for time-resolved electron diffraction (TRED) experiment," and A. S. Terekhov, et al. (*Institute of Semiconductor Physics of RAS*) "Computerized image intensifier testing system."

The first was dedicated to the theory and results of computer simulation of a crucially new electron-optical system with no steady electrostatic field, allowing considerable electron bunch compression in time. The method is based on the fact that perfect temporal photoelectron bunch focusing is realizable in time-dependent fields, being principally impossible in static ones. The focusing effect results in temporal resolution breakthrough, reducing the level of 200 fs (achieved in modern photoelectronics devices) to a few femtoseconds and even attosecond level. An electron bunch was successfully compressed to 8 fs in the latest experiments.

The second report describes a multifunction modular testing system, allowing approximately 40 parameters measurement of the 2^{+}–4^{th} generations II. Optical and electronic modules of the system are mounted on a single thermostabilized metal platform and are protected from external light. The optical modules, such as light sources, lens systems, a digital CCD-camera of a S1C model type with a 1225×1300 CCD sensor, are mounted on two separate biaxial platforms, supplied with stepping motors and position sensors. The accuracy of the optical modules positioning is better than 0.3 µm. A multispectral photodiode light source emits light at 11 wavelengths within the 450-1060 nm spectral range. It is used in the system to provide stability of density, spectral content and spatial homogeneity of the light bunch incident on a photocathode. Stability of digital CCD-camera quantum efficiency and noise characteristics is provided by thermostabilisation.

II parameter measurement is performed with the help of a control program. It displays a list of available measurement procedures for the parameter. On launching the selected procedure, the control program performs optical and electrical measurements and makes a test record of measured parameter values, measurement conditions, etc.

New approaches to measurement of some II parameters (resolution, halo, etc.) were discussed, as well as metrological certification problems.

Basic reports on night vision and optical devices were made by CCB Tochpribor, Katod JSC, FGUP NIIKI OEP, S.A. Zverev Krasnogorsky Zavod JSC, and GIPO RD&P Center.

An impulse night car driving system was designed on the basis of the second generation II produced by JSC Katod, which is connected with a CCD camera through optics. The system provides safety improvement for car driving during night-time. The device guarantees 215 m road and wayside visibility at 10^{-2} lx luminance and 40 m visibility in the fog. The system also protects the driver from the oncoming car's blinding light. The system field of view is $6^{\circ}\times 9^{\circ}$. The driver observes the road and wayside image on the monitor screen. To provide the device operation in a strobing mode, a special high-power LED light was designed. The worse the meteorologic conditions are, the shorter the impulse light length is.

A new digital night-time illuminometer is also presented. Methods of detection and suppression of optronic equipment are thoroughly discussed.

NIIKI OEP presented a summary of its experience in production of IR lens, catoptric and catadioptric objectives for the spectral ranges 3–5 and 8– 4 μm, which fit modern matrix photodetectors design. A complex technological process of their production is considered, as well as their output parameters measurement procedures.

Requirements are specified for blank initial check of optical elements (OE) made of materials, nontransparent in visible range. A comparative analysis of OE formation by diamond microturning and polishing is made. A centering technology for metal mirrors with aspherical working surfaces is described.

In a series of reports by A.I. Goev, et al. (*S.A. Zverev Krasnogorsky Zavod JSC*), prospects of new materials application for high-quality optical coating generation are at issue. The coatings mentioned are such as titanate gadolinium, titanate lutecium, zirconate gadolinium, and zirconate lutecium.

As hyperspectral optical medium it is suggested to use polycrystalline zinc selenide.

Photoelectronics optical materials and structures were thoroughly examined in the reports by O. N. Ermakov, et al. A review of new Russian organic materials was presented. Experimental data were shown concerning optical characteristics in the wide spectral range including optical absorption and luminescence spectra.

Two-layer device organic structures are studied. Data are presented on their current-voltage and photoelectric characteristics. It is determined that the structures are UV-sensitive, their photosensitivity maximum being at $\lambda \sim 380$ nm.

Problems of modern optical-electronic systems metrological provisions are formulated in the report by Y. I. Belousov (The Branch of Central Scientific Research Institute Cometa, Scientific Design Center Electro-Optical Surveillance Systems, St. Petersburg). In his opinion, these problems can be designated as determining next generation photodetector potentials and a system of parameters, which would be necessary and sufficient for modern and future photodetectors complete characteristics description.

Based on the present-day idea of the dynamics of optical signals generating, distribution and registration processes, a statement is issued that the next generation optoelectronic converters should be in position to adapt to current viewing conditions, that including not only exposure time, but also spectral, polarization characteristics, etc. Therefore, one of the essential features of next generation photodetectors is the ability for prompt characteristics alteration in order to provide optoelectronic converters adaptation to viewing conditions.

The second problem is associated with the first one. It lies in the fact that modern photodetector characteristics description contains too many parameters. They may be convenient for a particular designer, but don't allow to compare different photodetectors nontrivially or estimate their efficiency in optoelectronic converters application. A modern system of photodetector parameters and their measurement methods should be worked out in collaboration with photodetectors principal developers and consumers. Consideration must be given here to the present state and development prospects of IR devices.

Similar problems are considered in the previously quoted A.S. Terekhov's report. For the first time a series of reports on particularities of innovation processes in photoelectronics and the whole optoelectronic industry was delivered on the conference on photoelectronics. All of them were presented by Orion RD&P Center and realized under the guidance of A.M. Filachev and M.D. Korneeva.

In conclusion of this review of the XIX International Scientific and Engineering Conference on Photoelectronics and Night Vision Devices, it is necessary to note the high level of leading companies' achievements. It is possible to assert that the submitted reports cover almost the whole circle of problems facing this dynamically developing research-and-technology industry.

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REFERENCES

[1] XIX International Scientific and Engineering Conference on Photoelectronics and Night Vision Devices (May 23-26, 2006. Moscow, Russia). Abstracts. 192 pp.