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Concise review of recent advances and applications of the electron linear accelerator ELU-4 in scientific and technical fields

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The analysis presented in this concise review is directed towards evaluating the contemporary trends and practical implementations of the ELU-4 electronic linear accelerator across a broad spectrum of scientific and technological domains. The ELU-4 linear electron accelerator represents a key technological achievement in the field of accelerator technology in general and linear electronic accelerators in particular. Various aspects of the use of ELU-4 are considered, starting from its application in medicine, ecology, verification of computer models for calculating the effects of radiation, space applications, research on the effect of electronic irradiation on various materials and devices, including semiconductor devices, ending with its fundamental research of materials. Current data presented in scientific articles and reports from the last ten years are researched and analysed. This succinct review not only underscores the conventional applications of this accelerator but also underscores its potential in nascent fields of science and technology. The incorporation of ELU-4 into diverse research and engineering endeavors presents notable prospects for innovation and the advancement of scientific knowledge frontiers.

Key words: accelerator, electron, ELU-4, irradiation, radiation.
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1 Introduction

Electronic linear accelerators hold a distinguished position among the principal instruments in contemporary science and technology, offering unparalleled opportunities for investigating materials and processes at the molecular level [1-5]. Within this concise review, we aim to delineate the recent advancements and diverse applications of the ELU-4 electronic linear accelerator across various scientific and technical domains.

As a flagship representative of the current generation of electronic linear accelerators, ELU-4 garners attention in research domains concerned with the ramifications of irradiation on materials. It conducts experiments geared towards scrutinizing the effects of electron irradiation on a plethora of materials, encompassing semiconductors, composites tailored for space applications, and materials integral to radiation shielding endeavors [6-19].

Moreover, ELU-4 assumes a pivotal role in validating and complementing computational models, thereby fortifying their accuracy in matters pertaining to the effects of radiation on materials [20-22]. Furthermore, the accelerator finds utility in fundamental research endeavors aimed at elucidating the impact of irradiation on materials [23, 24] and the synthesis of novel materials endowed with distinctive properties [25, 26].

The principal objective of this article is to furnish an concise overview of the prevailing applications of ELU-4 in scientific research and engineering realms. We will delve into its contributions across a myriad of domains, encompassing materials science, radiation protection, space technology, and fundamental scientific inquiry. The outcomes and potentialities associated with ELU-4 usage signify a substantial stride towards the advancement of contemporary technologies and foundational scientific research.

2 Effect of irradiation at the ELU-4 electron accelerator on the electrical properties of materials

The work conducted by Mustafayev S.N. and co-authors focuses on investigating the repercussions of electron irradiation on $TlGaS_2$ single crystals, materials renowned for their responsiveness to visible and X-ray radiation. Following irradiation with varying doses of electron flux from the ELU-4 accelerator, operating at an energy of 4 MeV, ranging from $2.1\cdot10^{12}$ to $2.4\cdot10^{20}$ e/cm^2, notable alterations in dielectric properties and conductivity are observed. These alterations manifest in a reduction of the real component of the complex dielectric constant at elevated frequencies, an augmentation in conductivity, and a shift in the mode of charge transfer through localized states proximate to the Fermi level [27].

In recent years, there has been a burgeoning utilization of low-dimensional semiconductor materials, including 2D chalcogenides, in micro- and nanoelectronics, photonics, and spintronics. Investigating the impacts of X-rays, gamma radiation, and high-energy charged particle fluxes on the physical characteristics of semiconductor materials has emerged as an imperative task. Asadov S.M. and Mustafaeva S.N., in their research, scrutinized layered single crystals of gallium-containing chalcogenide (GaS), grown utilizing the Bridgman method, exhibiting p-type conductivity. These single crystals displayed a hexagonal lattice structure characterized by lattice parameters a = 3.58 Å and c = 15.47 Å.

The authors discerned trends in alterations of dielectric properties and transverse conductivity in layered GaS single crystals contingent upon electron irradiation with an energy of 4 MeV and diverse radiation doses ($2\cdot10^{12}$ and 10^{13} cm^2). It was revealed that irradiation engenders an augmentation in the real component of the complex dielectric constant, a reduction in the imaginary component, the dielectric loss tangent, and AC conductivity. Notably, at specific irradiation doses ($2\cdot10^{12}$ – 10^{13} cm^{-2}), conduction losses were observed in GaS. The modifications in AC conductivity in GaS, both pre- and post-irradiation, were attributed to the hopping mechanism of charge transfer along states localized proximate to the Fermi level, exhibiting a characteristic frequency dependence of AC conductivity on $f^{0.7\text{-}0.8}$ within the frequency range $f = 5\cdot10^4 – 10^7$ Hz.

Furthermore, it was found that at temperatures ranging from 140-238 K, layered GaS single crystals demonstrate hopping conductivity across their layers under a constant electric field, predicated on a variable hopping length along states localized in the vicinity of the Fermi level. At temperatures below 140 K, activation-free hopping conduction was discerned.

The analysis of DC- and AC-conductivity of GaS single crystals enabled the authors to estimate the density of states proximate to the Fermi level, their energy dispersion, average hopping distances, and activation energy. Additionally, the article investigated the impact of irradiation on parameters of states localized within the band gap [28].

3 Effect of electron irradiation on the characteristics of electronic components and devices

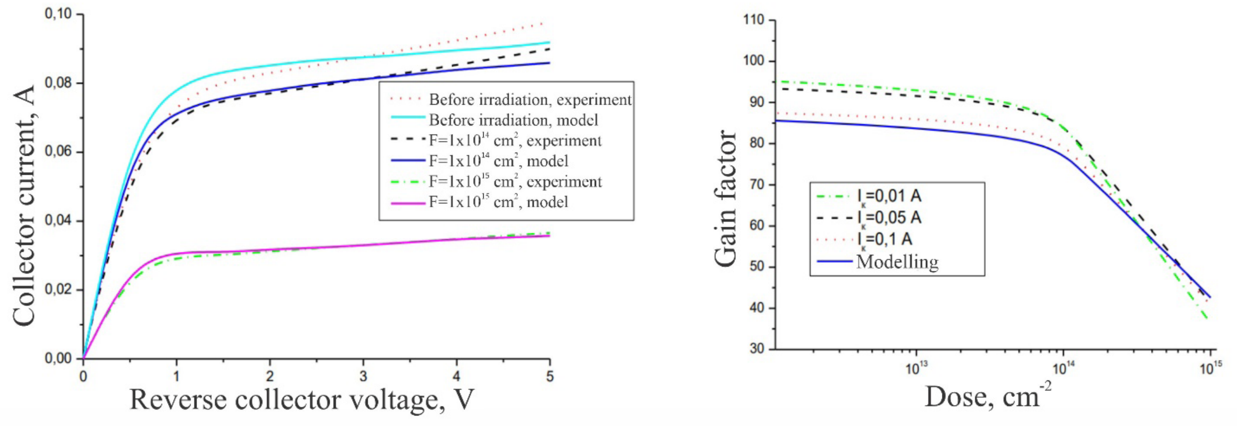
In their study, O. V. Dvornikov and colleagues [29] investigate the impact of a 4 MeV electron flux and gamma radiation from ^{60}Co on the characteristics of silicon complementary bipolar transistors (BT) and a broadband operational amplifier (OPA) constructed based on them.

The operational amplifier functions comprise a voltage-controlled current source, an output emitter follower, and PTAT (Proportional To Absolute Temperature) current sources. The circuit is designed with high radiation resistance mechanisms, including input current compensation, bias current stabilization, zero offset voltage minimization, and performance maintenance.

The authors conduct measurements on the current transfer coefficient, cutoff frequency, Early voltage, forward voltage drop across the emitter junction, current consumption, zero offset voltage, and open-loop voltage gain of both the BT and op-amp before and after irradiation. Notably, despite a significant reduction in the current transfer coefficient of the transistors, the op-amp parameters exhibit minimal change when subjected to ionizing radiation.

Their findings underscore that an op-amp constructed using complementary BT serves as a radiation-resistant analog device suitable for incorporation into systems tasked with preprocessing signals from multi-element photodetectors [29].

The work of Miskevich S. A. et al. concentrates on developing semiconductor devices resilient to ionizing radiation for application in nuclear power engineering and spacecraft. The authors have proposed a physical and mathematical model delineating the radiative alteration in the lifetime of charge carriers in silicon under the influence of a flux of 4 MeV electrons. They devised a method to calculate the change in hole lifetime and evaluated the electrical characteristics of a bipolar transistor post-irradiation. The results reveal a significant decline in the transistor characteristics upon irradiation with fast electrons. As depicted in Figure 1 and Figure 2, the developed model concurs with experimental observations, facilitating its utilization in software for modeling radiation-induced changes in semiconductor devices [30].



a

b

Figure 1 – Electrical characteristics of the transistor before and after irradiation with 4 MeV electrons [30]

In another paper, Miskevich S.A. et al. [31] investigated the spatial distribution of nonequilibrium minority charge carriers in bipolar transistors before and during radiation exposure. The analysis focused on the p-p-p bipolar transistor KT3107A manufactured by INTEGRAL JSC. The device irradiation was conducted using the linear accelerator ELU-4 with electron energy E_e= 4 MeV. The pulse duration was 5 µs, and the pulse repetition rate was 200 Hz. The electron flux density varied within the range of (5-10)10^{11} cm^{-2}c^{-1}, while the electron fluence ranged from $5{\cdot}10^{13}$ to $2{\cdot}10^{15}$ cm^{-2} [32].

Both modeling and experimental investigations revealed consistent results: a notable deterioration in the electrical characteristics of bipolar transistors upon irradiation with fast electrons of 4 MeV energy. This deterioration was evident in the decrease of output current and gain, along with an increase in base current (refer to Fig. 1b) [32].

Strelchuk A. M. et al. [33] conducted a study on the radiation resistance of commercial Schottky diodes based on silicon carbide (4H-SiC) with varying doping levels. Three types of diodes with differing levels of n-type conductivity doping were investigated. These diodes underwent irradiation with electrons and protons of different energies: 0.9 MeV electron irradiation was conducted at the RTE-1V accelerator, 3.5 MeV at the ELU-4 accelerator, and 15 MeV proton irradiation was carried out at the MHz-20 cyclotron.

Through analysis of current and voltage under forward and reverse bias conditions, the researchers identified several effects associated with the impact of irradiation on diode characteristics. Notably, they observed that the series resistance emerged as the most radiation-sensitive parameter across all diode types (refer to Fig. 3).

The researchers also observed a threshold dose of irradiation, below which the resistance practically remains unchanged. However, upon surpassing this threshold, the series resistance of the diodes exhibited a sharp increase, demonstrating a step dependence with an exponent ranging from 10 to 17, and reaching values of about 10^9 Ohm without signs of saturation. In contrast, the breakdown voltage and pre-breakdown current were less sensitive to irradiation and began to exhibit significant changes only at higher irradiation doses [33].

The study conducted by Bumai Yu. A. et al. [34] investigates the impact of high-energy charged particles on light-emitting diodes (LEDs) based on heterostructures. It demonstrates that irradiation with fast electrons (4 MeV) can induce defects in the diode structure, consequently affecting their optical and electrical characteristics.

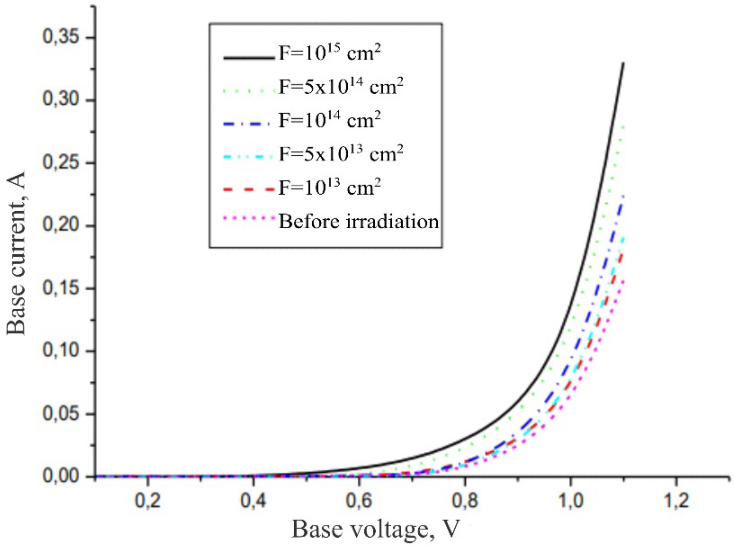


Figure 2 – Input characteristics of BT before and after electron irradiation [30]

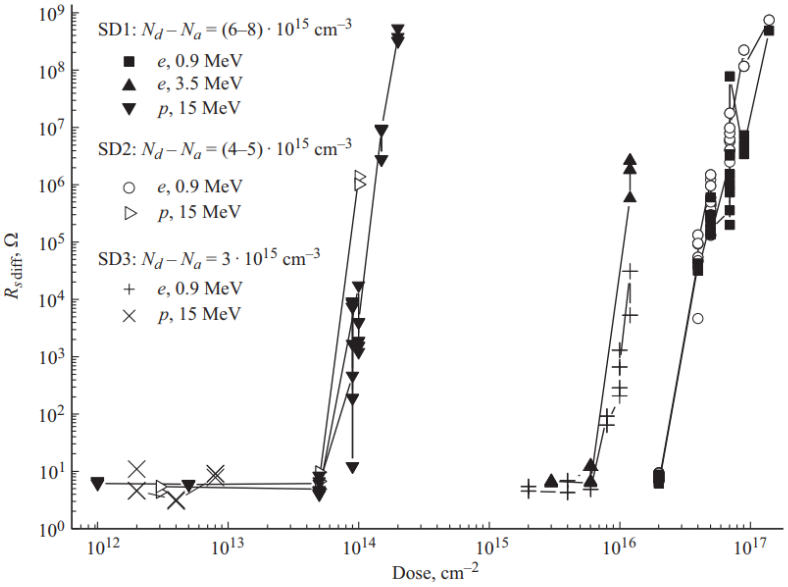


Figure 3 – Dependences of the series differential resistance of Schottky diodes of the first (SD1), second (SD2) and third (SD3) types on the irradiation dose by electrons (e) with energies of 0.9, 3.5 MeV and protons (p) with energy of 15 MeV [33]

Various Helio LEDs (1 W) with differing luminescence and low-power Nichia LEDs (90 mV) were employed in the experiment. Irradiation of all diodes was carried out using an ELU-4 accelerator with varying parameters of electron energy and fluence.

The findings of the paper reveal that nitride-based LEDs exhibit greater resilience to degradation under irradiation compared to phosphide-based LEDs, particularly in the red color range. Alterations in the light emission spectra and Urbach energy suggest a potential increase in defects at the interfaces.

Furthermore, the authors observed that with increasing fluence of fast electrons, the temperature of the electronic subsystem decreases for nitride LEDs but increases for red diodes, thereby influencing their luminous characteristics.

In conclusion, the study underscores the influence of irradiation on the electrical and optical properties of diverse types of light-emitting diodes. It delineates patterns of changes under irradiation and speculates on the feasibility of restoring the optical power of irradiated nitride-based diodes [34].

4 Application of ELU-4 for space applications and radiation protection

Materials employed in space applications are subject to electron fluxes spanning a broad energy spectrum. These particles can induce thermal ionization within dielectric materials, leading to the accumulation of uncompensated electric charge, thus engendering radiation electrification and substantial alterations in dielectric electrical properties. Consequently, the electrical breakdown of dielectrics stands as a primary cause for the malfunction of electronic and electrical spacecraft equipment. N. I. Cherkashin's study [35] is dedicated to investigating the impact of a beam of fast electrons on a polymer composite utilized for cosmic radiation shielding.

Utilizing the Monte Carlo method and conducting experimental irradiation of composite samples at the ELU-4 electron accelerator, the author reveals that the depth of maximum accumulated energy concentration within the composite varies: 1.5 mm for electrons with an energy of 1 MeV, 2.7 mm for 1.5 MeV, and 4.6 mm for 2 MeV. Relative to protective materials comprising heavy metals like lead or bismuth, the effective range within the considered composite is several times greater. Additionally, the intensity of bremsstrahlung radiation is notably reduced, representing an advantageous characteristic compared to heavy metal-based materials.

The study demonstrates that a polymer composite consisting of fluoroplastic filled with modified bismuth oxide exhibits high radiation resistance and protective efficacy attributable to the presence of a space charge [35].

In the work by Panyushkin N.N. [36], the feasibility of calculating and experimentally predicting radiation dose effects and the radiation resistance of CMOS integrated circuits (ICs) is explored. The approach centers on utilizing predetermined parameters – specifically, the initial switching voltage and the absolute increase in power source current post-radiation testing.

The article highlights that prevailing methods for predicting product durability necessitate sample irradiation and prolonged annealing at elevated temperatures. In contrast, the author's method obviates these processes, relying instead on initial values of select electrical parameters controlled during product fabrication. This methodology enables the determination of product durability via test exposure to ionizing radiation both before and after irradiation. The resultant measurement data facilitate the development of models ensuring product radiation resistance aligns with technical specifications. Two parameters – threshold switching voltage and current consumption – are utilized for prediction due to variations in production lots and sample sensitivity to radiation effects. The method hinges on theoretically and experimentally ascertaining the radiation resistance of CMOS integrated circuits utilizing initial values of predicted electrical parameters controlled during production.

Experimental data concerning the CMOS IC 564 LE5, comprising five samples of 2 NOR gates, were employed. Irradiation was conducted using the ELU-4 linear electron accelerator with an energy of 4 MeV within a fluence range spanning 0.1 to 3.0 times the critical electron flux for this IC type. The study yielded the following outcomes: a predicted error of approximately 7% for the threshold switching voltage and about 4% for current consumption. These values closely align with measurement error, affirming the method's efficacy in selecting more resilient samples and ensuring requisite radiation resistance [36].

Bogatyrev Yu.V. and colleagues [37] present findings from studies on radiation protection utilizing tungsten-copper composites. The efficacy of these shields is evaluated based on transistor parameter changes under electron irradiation, with absorbed dose in the IMO crystal being calculated. Experimental evidence demonstrates that these screens reduce radiation by factors ranging from

10 to 10^4 in the energy range of 0.5-6 MeV. The experimental methodology encompasses screen fabrication, morphological and chemical composition analysis, and irradiation using the ELU-4 linear electron accelerator (refer to Figure 4).

The authors have successfully developed W77.5Cu22.5 composite materials through solid-phase synthesis for application as radiation shields in metal-ceramic integrated circuits (ICs). These materials exhibit excellent solderability using inert fluxes and comply with contemporary technological requirements. Experimental investigations in the study demonstrated that shields ranging in thickness from 1.21 to 1.49 mm yield maximum shielding efficiency (K, = 143-155) for p-MOS transistors like IN74AC04.

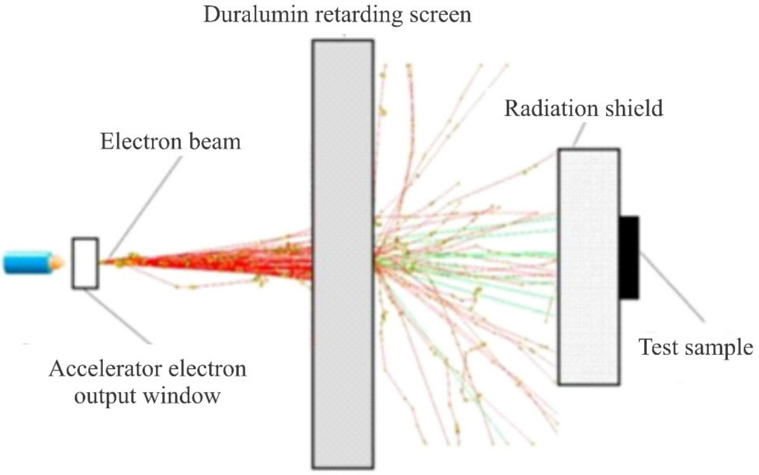


Figure 4 – Schematic of radiation shield testing [37]

Modelling efforts conducted by the authors illustrate that the developed $W_{77.5}Cu_{22.5}$ screens effectively attenuate electron radiation within the energy range of 0.5 to 6 MeV (K,4040). Regarding protons of cosmic origin (with energies spanning from 0.04 to 500 MeV for a 60° orbital inclination and a circular orbit at an altitude of 300 km), these screens provide up to a 6-fold reduction in absorbed dose.

Furthermore, the study reveals that the effectiveness of radiation shields may vary depending on the orbit type. Optimal results were attained in orbits characterized by high electron contribution, such as GEO, GLONASS, and VEO. Conversely, for orbits with a predominant proton contribution, like ISS and circular polar orbits, the screens exhibited reduced efficacy.

Overall, the research findings underscore the promising potential of the developed material and technology for fabricating more radiation-resistant enclosures for the next generation of electronic components utilized in rocket and space technology [37].

In their work, D. I. Tishkevich et al. [38] underscore the significance of bismuth as a promising material for safeguarding microelectronics products from ionizing radiation. Studies reveal that bismuth coatings exhibit distinct crystalline structures that evolve with increasing thickness and the introduction of various additives. Experimental investigations demonstrate the high efficacy of bismuth shields at specific thickness values (around 2 g/cm²) and attenuation coefficients (equal to 156).

Particular emphasis is placed on the potential of bismuth for radiation shielding, considering its intrinsic properties and optimal exposure parameters. The fabrication technique for these coatings involves electrochemical deposition, supplemented by Ni-P chemical deposition to enhance adhesion. Experiments investigating the radiation-protective properties of bismuth-based shields on test structures of p-channel MOPTs (CMOS IC elements) subjected to electron irradiation with energies ranging from 1.6 to 1.8 MeV and exposure doses up to $5 \cdot 10^{14}$ cm^2 indicate that as the reduced shield thickness increases from 1.1 to 2.7 g/cm^2, the shielding efficiency coefficient Ke rises from 95 to 165. The relationship between Ke and reduced thickness can be modeled by a second-degree polynomial. Optimal values of reduced thickness, considering mass and dimensional parameters, lie approximately within the range of 1.7-2.0 g/cm^2. Beyond a thickness of 2 g/cm^2, increasing shield thickness does not significantly enhance Ke, primarily due to the prevalence of absorbed dose from braking radiation by the protected samples.

The paper concludes by accentuating the potential efficacy of bismuth as an efficient material for radiation protection in microelectronics [38].

It is noteworthy that contemporary space exploration is poised on the brink of pioneering new spacefaring technologies. Nations such as the United States of America, Russia, Europe, China, and Japan are vigorously pursuing the discovery and development of novel structural and functional materials to enhance space technology systems. Both fundamental and applied research endeavors are underway, spanning the realms of near and deep space, to facilitate the study and peaceful exploration of outer space. Concurrently, ground and space infrastructure is being established and refined, while innovative technologies are being forged in diverse domains including space materials science and instrumentation, natural resource and geophysical monitoring, and space biotechnology and medicine, with the aim of addressing the socio-economic challenges facing spacefaring nations.

The involvement of Kazakhstani cosmonauts in space experiments aboard manned complexes has yielded invaluable findings, laying the groundwork for the emergence of a novel scientific discipline in Kazakhstan: space materials science and instrumentation.

Therefore, in the study by Musabayev et al. [39], the findings regarding the comprehensive effects of outer space factors, including radiation, on materials and the devices derived from them are presented. The paper delineates a model illustrating the effects of single heavy cosmic ray nuclei (CRN) on components of onboard electronic equipment. Typically, extensive groundwork is conducted under terrestrial conditions to simulate the radiation effects on materials employed in space equipment before embarking on space experiments aboard manned complexes.

Given the aforementioned context, it is imperative to investigate the influence of space radiation, including its electronic component, on materials and associated devices under terrestrial simulation conditions. Linear accelerators, cyclotrons, synchrophasotrons, and other radiation sources are commonly employed for this purpose.

5 Effects of irradiation on materials, defect formation and synthesis of new materials

The paper by Voitovich A. P. et al. [40] delves into the characteristics of radiation-induced defects in crystals, their utility in the detection and measurement of ionizing radiation in electronics, and the potential application of nanocrystals harboring such defects as biological sensors. The researchers irradiated wafers with a robust stream of high-energy electrons, possessing an energy of 4 MeV and a fluence of 10^{13} electrons/cm^2, at room temperature utilizing an Electronica ELU-4 linear electron accelerator for several seconds. This irradiation induced defects in the material; however, these defects did not propagate far enough to interact with other parts of the material and elicit reactions. The authors demonstrated that the fragmentation of irradiated LiF crystals engendered new defects, with the concentrations of these defects remaining stable at room temperature for prolonged periods. Furthermore, UV irradiation on nanocrystals subsequent to the completion of center formation processes significantly amplifies the defect concentration. Additionally, various radiation defects were observed in unirradiated nanocrystals, underscoring the significance of processes occurring during crystal fragmentation [40].

Naumova O. V. et al. [41] conducted a study to investigate the impact of ionizing radiation on mineral raw materials used in silicon production, a crucial material in solar energy applications. The experiment involved irradiating chalcedony powder with braking gamma-rays using an accelerator. The duration of irradiation was determined by the accelerator parameters, including beam current, power, and distance to the irradiated object.

This nano-exposure technique facilitated the intensification of production processes, leading to alterations in the material's microstructure and the formation of structures characterized by high homogeneity, density, and uniform distribution of impurities. The mechanism underlying the effect of braking gamma-rays on powder raw materials lies in their potent and diverse impact.

The authors assert that the developed methodology, based on irradiating raw components with braking gamma-rays, has demonstrated the possibility of controlled alteration of material properties, which holds significant scientific and practical importance. This approach enables the production of materials with unique properties inaccessible by existing methods.

Moreover, the authors suggest that utilizing accelerator technology as a "tool" for controlling complex processes in manufacturing presents novel opportunities for addressing important challenges, including enhancing the parameters of semiconductor structures.

The article presents an experiment that, for the first time, enables the examination of structural changes occurring in mineral raw materials during the production of polycrystalline silicon under the influence of ionizing radiation. The findings of the study are expected to enhance the technologies for deep processing of rock-forming minerals based on chalcedony, leading to more effective enrichment and purification of raw materials during silicon production.

These results highlight remarkable changes in the structure of technical silicon products achieved using radiation technology. With the high homogeneity of the obtained materials, it becomes feasible to fabricate solar cells with reproducible parameters for new light-emitting devices.

Furthermore, the study revealed the potential of obtaining nanostructured materials in the creation of complex silicon structures incorporating alloying additives. This advancement could lead to the production of photovoltaic cells capable of efficiently harnessing the entire spectrum of solar energy [41].

6 Application of the ELU4 accelerator in the verification of computer models to assess the effects of electron irradiation on materials

The scientific team led by Prof. Pivovarov Y.L. at Tomsk Polytechnic University has undertaken several studies in recent years focusing on various aspects of the interaction between relativistic electrons and ions with oriented crystals.

In theoretical studies and computer simulations reported in [42-45], investigations were conducted on the scattering of 255 MeV electrons by axial and in-plane channeling in silicon crystals. Experiments were conducted at the linear accelerator of the synchrotron SAGA-LS (Japan). The simulation outcomes exhibit good agreement with experimental data, indicating the applicability of the utilized models in the computer code developed by the authors [46].

Another series of works explored the generation of photons possessing orbital angular momentum, known as twisted photons, using different emission schemes. These twisted photons offer additional degrees of freedom and can potentially overcome the diffraction limit, increase the bandwidth of telecommunication channels, and facilitate quantum cryptography. Calculations presented in [47] evaluated the probability of emission of twisted photons by axially symmetric particle clots, while [48] demonstrated that transient radiation and Vavilov-Cherenkov radiation possess orbital angular momentum for narrow relativistic Gaussian beams of electrons and ions. Additionally, investigations in [49, 50] examined the generation of twisted photons in axial and in-plane channeling of 255 MeV electrons in thin silicon crystals. The periodicity of the projection of the total angular momentum of a photon as a function of photon energy was also uncovered in [50].

In a separate line of inquiry, theoretical studies were conducted on positron generation utilizing a hybrid scheme [51]. In this scheme, electrons pass through an oriented crystal (silicon or tungsten) to generate radiation, which is then fed into an amorphous converter where electron-positron pairs are generated. These studies, detailed in [52], encompassed computer modeling for both coherent and incoherent braking radiation in crystalline targets of silicon and germanium. Calculations were performed to determine the optimal thickness of the converter for maximal positron yield, and the energy spectrum of emitted positron beams was calculated for the optimal converter thickness.

These research endeavors hold relevance for the ELU-4 accelerator. Conducting similar investigations with the ELU-4 accelerator could unveil novel characteristics of relativistic electron treatment and enable the production of radiation with unique properties.

7 Conclusions

In conclusion, electron linear accelerators, notably the ELU-4, stand as indispensable assets in contemporary scientific and technical exploration. The comprehensive review and analysis of data underscore the broad spectrum of applications afforded by the ELU-4 across diverse fields of science and technology.

Foremost among its applications is the probing of material responses to electron irradiation. This facet finds utility in investigations spanning semiconductors, space-grade composites, and the characterization of radiation shielding materials. The ELU-4 furnishes an optimal environment for such studies, facilitating nuanced examinations of material behaviors under varying irradiation levels.

Moreover, electron linear accelerators have proven instrumental in tasks ranging from validating computational models and assessing radiation shielding materials to fundamental inquiries into irradiation effects and materials synthesis. These endeavors constitute pivotal pillars supporting the advancement of contemporary technology and the frontiers of scientific inquiry.

In light of these findings, the ELU-4 emerges as a versatile and potent tool across scientific research and engineering domains. Its exceptional capabilities in electron irradiation, coupled with cutting-edge analytical and modeling methodologies, position it as an indispensable resource for the scientific and engineering community. It remains at the forefront of innovative research and development endeavors, driving progress and fostering breakthroughs in knowledge and technology.

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