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APPLICATION OF WIRELESS MONITORING AND COMMUNICATION SYSTEMS IN THE POWER ENGINEERING

The article describes some achievements of modern radio electronics, which prove a huge potential of modern wireless engineering for using in the fuel-energy complex. Wireless corporation communication systems, application of short-range radar measuring systems on the power engineering objects, prospects of laser measuring systems, methods of radio thermography and radio spectroscopy, wireless acoustic-electronic sensors are discussed.

Keywords: radio communication, wireless sensors, short-range radar, laser measuring systems, radio thermography, radio spectrometry, acoustical sensors.

At present, our world goes through the period of the impetuous scientific-technology revolution, which can be called “wireless revolution”. Now the radio signal plays a significant role not only in radio and TV broadcasting but in various scientific researches, in industry and in private life. The complex radio engineering devices have fixedly entered into everyday life: cellular phones-communicators, wireless phones, satellite and cable TV systems, the mobile Internet, smart cards etc. The radio engineering systems for guarding and warning are installed not only on guarded objects but also in private houses. Motor cars are equipped with complicated systems of guarding and radio navigation. Radio-frequency identification sensors are not only used in logistics but in miniature variants are even used as implants for domestic animals. There are stupendous achievements in creation and development of modern communication systems intended for transmission and reception of both speech signals and digital data.

It is natural that at this level of distribution of radio electronic devices the environment is saturated with the huge quantities of radio signals. These signals coexistence without creation of interference becomes more and more complicated. Problems of ecology arise more sharply as well. Up to now, the problems of electromagnetic compatibility of radio electronic equipment of different destination are nor solved, nither is the problem of electromagnetic radiation influence of different nature on the human organism. So, for instance, the authors of [1] make a conclusion that the development of microwave communication systems in the near future may cause the appearance of a new sub-field in ecology — electromagnetic (microwave) ecology.

It is clear that during such a scientific-technological revolution it is impossible to pass over the areas of power engineering traditional for our country, especially under conditions of the critical situation existing during last decades in connection with renovation of strategic power engineering equipment. It is unlikely that the simple doubling of the operating equipment is the best way to solve the problem of industry renovation now when new scientific, manufacturing and technological possibilities promise serious hitch solutions for reconstruction of obsolete equipment or construction of new objects. The experience of the last decades shows that the simple purchasing of western control and monitoring equipment oriented to another conditions and systems will hardly help us strategically. Our country should develop its own multifunctional systems for control and monitoring of the important objects, and it should be done by its own scientific and industrial forces. It is possible subject to close cooperation between scientists and industrial experts of different areas including specialists in wireless systems, i. e. in the field of radio electronics.

In the present paper an attempt has been made to substantiate the necessity and availability of joining efforts and experience of power engineering and radio electronics experts. For radio engineers of the National Research University «Moscow Power Engineering Institute» **(MPEI)** publication of the brief review of their research and develop-

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ment results oriented to the fuel-power complex means a possibility to describe in short the promising directions of such cooperation.

It is no secret that during the previous years our researchers and engineers in radio engineering field were investigating and developing unique systems mostly for the military-industrial complex. The process of implementation of radio engineering into the peaceful industries (including power engineering) was always slow and hesitating because radio engineering experts did not understand the needs of those industries and the achievements of radio engineering were not open to the power engineering experts. Now the situation is changing for the better and many achievements of radio engineering will be without fail needed by the powerful energetics.

Application of wireless communication systems in power engineering

Let us consider the opportunities of radio communication systems application in power engineering. From the point of view of the application scale, they can be divided into two large groups: global communication systems and systems of intra-object radio communication.

The global systems in the thermal power engineering complex can be built, as usual, using the communication satellites. But the fuel-power complex has the unique possibility to develop their own corporate communication networks since it has in its disposal an extremely branched network of electric transmission lines, oil and gas pipe lines. For instance, the application of ground wires with internal fiber-optical cables provides unique possibilities for creating cheap communication links belonging to the power engineering industry.

Global networks are used for telemetric information transmission from one object to another or to controlling centers, as well as official control and monitoring information transmission. So-called “dark fibers” (i.e. not used fibers) can be leased successfully and provide serious benefits (especially in the future, when the role of the information transmission will be even greater). It is very promising to use power engineering communication channels for the distant education (e. g., retraining of specialists, distant knowledge monitoring, distant operator training) or for monitoring of the operator’s functional conditions.

Intra-station communication systems serve to organize both systems for personal speech communication and transmission channels for technological and control-monitoring information for the automated control system for technological process (**ACSTP**).

With transition of electric power usage to market principles the electric power consumption schedules (during 24 hours, a week and a month) have changed essentially, and now the consumption depends not only upon the manufacturer’s needs but also upon the financial condition of the enterprise. It is clear that this leads to sharply changing consumption schedules, which affects the reliability and amortization of power engineering equipment. In recent years the role of automatic control systems and automated systems for engineering diagnostics of equipment becomes very significant.

To optimize the operation mode of the modern power plants, the measurement of 3—4 thousand parameters is required, which cannot be ensured by the personnel and requires automatic methods. The modern ASCTP require a huge number of cables, and the complicated cabling essentially decreases the operation reliability and requires more expensive equipment. Evidently, it is impossible to create a reliable and effective ASCTP without systems of high-speed information transmission.

The relevant problem of effectiveness of power consumption can be also solved by the radio electronic facilities, e. g., those developed and marketed by the company «Schneider Electric» (Germany).

A wireless system of data transmission from power engineering objects was developed in MPEI [2—4]. The system has a possibility of rapid deployment and good noise-immunity. Earlier, a very simple and cheap radio system for single-direction low-speed transmission of alarm signals had been developed and a small consignment of such systems (50 complete sets) had shown good operation. After that, much more modern and complicated radio systems were developed for mobile diagnostic labs such as «Power-Microbus» and «Ecology-Microbus». These systems include three subsystems:

— gas analysis (for remote control of the gas composition, e. g., for ecology monitoring);

— electric energy quality check;

— heat control (measuring distributed heat fields and transmitting information through radio-modem communication line).

These subsystems are available in MPEI as working models.

Configuration of the developed systems implies a central post and a certain number of peripheral on-duty posts. The equipment of the central post is installed on a transport vehicle or permanently on the power engineering object while the equipment of the peripheral posts can be mobile and can be located where it is needed. Communication between the posts is realized through the wireless radio communication channel. The system is controlled by a PC program from the central post. The PC gathers all information and registers it in the database for the further analysis.

The result of our last development in this area is the distributed system for information transmission for spatially extended industrial objects, in particular for power engineering equipment such as turbines or boilers. Here a new engineering solution is of interest — combined application of local cable systems for data acquisition and storage in the high-speed standard RS485 and wireless radio modem communication line.

At present, the first phase of development of the radio system for information acquisition for the system of automated working place of the steam-boiler operator is fulfilled. This system is intended for Co-Generation Electric Plant (**CGEP**) of MPEI. The information from sensors will be transmitted through the radio channel from CGEP of MPEI to the operator's screen. We assume that at successful development of this investigation its results may be needed on different CGEP and on different objects of industrial heat supply. Similar systems can be used as reserve systems with autonomous power supply, which should essentially increase the "survivability" of equipment in emergency situations or in case of cable damage.

A diagnostic wireless information-measuring complex for the express-inspection of parameters of thermal and nuclear power plants or other extended industrial objects has been developed. This complex provides a real time information transmission from sensors through the radio channel to the central operator post located at several hundred meters' distance. Here the information is processed and accumulated in the database with possibility of further display on a PC screen in tables, graphs and diagrams. Operation parameters of this system are regulated by the operator.

Of course, taking into consideration the rapid development of the element base for implementation of modern radio engineering equipment, the above-mentioned models require modernization. However, this circumstance is not a problem because our developers have all necessary information and fulfill the similar investigations for other industrial branches. Thus, for a long time we have been developing a specific miniature system meant for transmission through the radio channel of discrete information about the heat network condition in Moscow residential neighbourhoods for further data processing, which will make it possible to control the parameters of these networks. It should be noted that as more perfect methods of information processing appear and the element base gets renewed, the developers modernize this system and implement its new variants successfully into Moscow municipal services.

The modern microelectronic element base opens new opportunities for creation of miniature (from 10 to 100 cm^3 in volume) measuring transducers with autonomous power supply and with transmission of measured parameters through radio communication channel, which allows to create extensive sensor networks at small expenses. In such measuring transducers we may use inexpensive (from 15 to 500 rubles or \$0,5 to \$12) microminiature (from 3 to 30 mm^3 in volume) integrated measuring sensors with the digital output signal of such parameters as temperature, pressure, moisture, illumination, acceleration and vibrations, as well as such electric quantities as voltage, current, power and frequency. Such sensors have high accuracy (0,3—3%) and small power consumption (about 0,3 mW in the active operation mode). They have a possibility to accumulate, process and transmit information by means of a micro-controller with an embedded or external radio modem.

At such power consumption and size, the sensors can be supplied with power from a small autonomous source, which allows to mount them easily on the equipment being operated since there is no need to construct power and communication lines and to operate during many months. A wireless measuring-information network for remote monitoring and remote control is built on the basis of measuring transducers. These devices can be successfully combined with control, energy saving and commercial accounting systems.

Let us discuss another series of developments, which was fulfilled with orientation to law-enforcement bodies, fire brigades, special groups for struggle against terrorism. These are radio-equipped protection helmets with internal non-visible antennas [5], which ensure reliable speech communication between subscribers. Taking into consideration the interest in the use of such systems of the service personnel of extended power engineering objects, the new variants of protection helmets were developed corresponding to the safety standards on power engineering objects.

Radar technology application in power engineering

With the help of radar technology we may solve many relevant problems in power engineering complexes [2, 6—9]. Let us consider a simple example.

In the operation process of a thermal power plant (**TPP**) water contaminated with mazut is generated. This water is accumulated in a reservoir, precipitated in it until the liquids are separated and then wasted. At that the water discharge should be interrupted before the mazut is wasted. In other words, the water level mustn't be allowed to fall below the minimal value. For this, we can use a supersonic sonar distance meter. In this case an ultrasonic radiator is placed on the bottom of the reservoir, the oscillations reflect from the surface of the water—mazut boundary and are received by the sonar. Then a measuring system determines the time of signal passage and, knowing its velocity, calculates the water layer thickness.

Such a sonar device was developed in MPEI [8] and it is able to measure the water layer thickness from several centimeters to several meters. Its cost at small-scale manufacture does not exceed \$200—\$250.

Supersonic sonar devices can be also used to measure levels of different technological liquids and paste-like products with the aim of automation of technological process control and monitoring. In this case the sonar is located on the reservoir cap and the beam of acoustic waves is directed to the surface of the product. The distance to the surface is measured and the product level is calculated. Measured values can be transmitted via wires or through radio channel practically to any distance. The level measuring error does not exceed 1—2%.

Radar devices, in which the radio-frequency radiation is used, are more sophisticated. Their operation principle is the same as in supersonic devices, but the measuring error is less. At present, in oil tankers, in oil and gas industry, on TPP the foreign level meters made by KROHNE (Germany) and SAAB Electronics (Sweden) are widely used. In MPEI as part of the program «Conversion and High Technologies» a high-precision radar level meter has been developed. It is the radar of continuous wave radiation with frequency modulation of the probing signal. The high accuracy was obtained owing to the application of the original algorithm of radio signal processing. The measurement error of the developed level meter is much less than the measurement error of the level meter B-70 from German company KROHNE.

The precision radar level measurer for liquid products with measurement error of the order of 0,1—0,2 mm has been designed. There are no such devices neither in Russia nor in foreign countries. These devices can find an application at petrol stations, petrol storages, chemical industries. The mentioned accuracy allows to measure the amount of petrol in standard (3×3×6 meters) reservoirs with an error down to 0,9 litres. Other versions of radar level meters for liquid and friable products have been developed. These devices are now successfully used at power engineering enterprises.

At present, dynamic parameters measurement methods based on application of different types of sensors are used for vibration inspection, investigation and alignment of turbounits. However, when it is necessary to measure at large temperatures and large pressures, typical sensors become very unreliable. Moreover, it is very difficult to conduct measurements in hard-to-reach places, for example, it is difficult to measure ripples of steam pressure in the nozzle box or in the internal case of the turbine. It is often necessary to make a rapid analysis of shafting vibrations of a turbine (or a pump or other equipment with the rotating elements) using short visible parts of the shafts. Elements of valve boxes and throttles of regulating valves of power engineering aggregates are difficult to access for measurement of dynamic displacements.

Achievements of radar technology allow to suggest new methods and fulfill high-precision measurements of small displacements (down to several microns) or establish the connection between pressure ripples and displacements of the sensitive element. It is especially important when measuring modes of powerful power engineering equipment (for instance, powerful turbine shaft beats) at typical pressure values (up to 240 atmospheres) and for strongly overheated steam (up to 400°C). One can reach it by usual methods only when using complicated cooling systems for the sensor.

A measuring device based of the precision radar level meter system allows to measure small displacements (several millimeters) with an error of several microns. Its application opens entirely new possibilities in diagnostics of steam turbines. A vibration meter and a steam pressure meter based on the measuring system of small displacements [6] have been developed.

The probing signal passes into the waveguide and is directed on the vibrating element of the turbine. The open end of the waveguide is located at the distance of 1—2 mm from the vibrating element, therefore the radiation area is very small. This increases the measurement accuracy and allows to measure vibration of any point of the surface. Since the waveguide can be bent in any manner, it can be located inside of the turbine case, which permits to measure continuously the vibrations of construction elements during the normal operation and to obtain the dynamic pattern, for example, of the shaft bending.

To determine the steam pressure, there is a membrane on the end of the waveguide, which bends under pressure. The value of the bend is proportional to the pressure and can be determined by radar meter of displacement. Thus, we can determine the steam pressure in any point inside the turbine case.

During development of the radar system of small displacements measuring the laboratory testing of the device model was conducted, which confirmed theoretical results and showed the device efficiency.

A series of portable devices for inspection of the gas contain (oxygen, carbon and nitrogen oxides, methane and other gases) has been developed. Both single-component and multi-component gas-analyzers have been created. The main feature of these devices is effective application of microprocessor engineering and smart signal processing allowing to take into account the change in temperature, pressure and moisture of environment and to compensate measurement results. Devices have high spark and explosion safety confirmed by official certificates. The good performance is achieved owing to original circuitry, technological and constructive solutions. The developed multi-component gas-analyzer with elements of artificial intellect has no (according to our information) analogues in the world [3].

Another interesting idea is related to results of almost thirty-years' investigations of ground and water surfaces by radar technologies from the flying vehicles. Re-orientation of these researches to the civil applications allowed to create the unique multi-functional radar measuring system PULSAP [10, 11], which may be used rather widely. This complex has a portable small-power radar of millimeter wave range. Its distinguishing feature is the application of phase methods of signal processing. This radar was successfully used for remote diagnostic of structure and parameters of plasma jet at the jet engine output. It turned out that radar monitoring of powerful equipment condition, which may be executed around the clock, allows to discover the vibration deviations from the rated level and permits to estimate the main spectral components and their dependence upon temperature and steam pressure. This allows to fix the increased beats, which are extremely dangerous for the operating turbine. With the help of this device, the determination of the live-steam pipeline deterioration on a Moscow TPP was fulfilled remotely, as opposed to the commonly used method which requires the full shutoff of the boiler, during which a fragment of the pipeline is cut out and then again welded. The used remote inspection method is based on the obtaining of a «vibro-portrait» — investigation of vibration spectrum on the chosen part.

One of the very interesting and noval applications of PULSAR radar is concerned with its possibility to estimate remotely the functional condition of a human being and to register the exit of some medical parameters beyond the permissible boundaries, which may cause the person to estimate the situation wrongly and to make a wrong decision. It is clear that this permanent inspection is extremely important for operators of huge power units. The radar allows to inspect the state of the operator right at working place without attaching any sensors. It means that his movements will not be limited. The duration of inspection can be arbitrary — from several minutes for the express-analysis to the full working day for estimation of fatigability. The power of radiated signal is very low and therefore it will not harm the operator. The radar can be located in the standard case near the operator or even mounted in the chair back. After finishing the inspection defined by the program, the computer of the device decodes the data obtained and allows the conclusions about operator efficiency, about his reactions on the current or on specially arranged extreme test situations. The obtained data about each inspected operator can be transmitted through the usual communication channels (including radio channel) or through the Internet to the centralized databank. At present this device is actively used for investigation of higher nervous activity of a man and for pre-flight inspection of astronauts. This device was awarded by the medal of International Exhibition in Brussels in 1997. There is no analogue of this device in the world.

Application of lasers in power engineering

Laser measuring systems are widely used to execute non-contact measurements of dynamic parameters of machine units as well as liquid and gas flows. At present, such systems are widely used both in scientific experiments and in industrial technologies, including observation of power engineering equipment operation and environmental monitoring and diagnostics [12]. Parameters measured by these systems are the most significant features of operation of hydraulic units, steam and gas turbines. The measurement results can be used both for optimization of operation modes and for opportune revelation of dangerous aperiodicities.

These systems play an important role in solving the problem of ensuring trouble-free operation and ecological safety of power engineering objects, and in their operating efficiency increase. The advantage of laser measuring systems is the applicability of remote, non-contact measurements, which do not disturb the measurement medium.

Investigations and developments of fiber-optic velocity sensors for liquid and gas flows were being carried out in MPEI since 1990s. These developments were based on application of semiconductor lasers and new elements of fiber-optic technology [13], new digital methods of processing of interference and Doppler signals of laser information-measuring systems [14]. For Doppler signals, which are registered under conditions when the law of signal phase differs from the linear one (in two-phase flows, in hydrodynamic flows in the presence of the acoustic field etc.) the new parameters estimation algorithms has been developed and investigated. The software packages based on different mathematical models of Doppler signals [15] have been created for estimation of mean and instantaneous values of frequency using different methods (digital spectral analysis, Gilbert transformation, discrete counting, wavelet analysis).

The main distinction of developed algorithms is the possibility to obtain estimates of nonstationary (pulse) signal parameters in the presence of multiplicative noise. The estimable parameter is the instantaneous frequency of signals (measurement results are given in relative units — the ratio of measured frequency to signal sampling frequency).

The laser optical-electronic sensors and the hardware-software means for data input and processing developed in MPEI allow to register vibro-oscillation of the object surfaces as well as hydro-acoustic oscillations with amplitude of a few hundredths of a micrometer, and to investigate their character in applied shock mode [16—18]. In this case, the measuring volume may be of several tens of microns in size, which is essentially less than when using the radio frequency waves (measuring volume is a region of space, in which the information signal is formed as a result of interaction of probing radiation with the test object). It makes it possible to take measurements with high spatial resolution.

Applications of radio thermography and radio spectroscopy

The radar complex for detection of oil and other grease films as well as higher temperature flows and solid impurities on the surface of water bodies is an example of radio thermography method application. This radar is based on the same PULSAR device, which in this mode registers the power flow of intrinsic thermal radiation created by a physical or an engineering object or a living organism. Absence of the direct contact makes it considerably easier to create the temperature fields maps and to analyse their dynamics. It is possible to obtain not only surface but depth thermograms. It might be useful, for instance, in the research of the Earth surface from the outer space. After modernization this method can be used for the search of survivors inside collapsed buildings.

The following interesting project [19, 20] demonstrates the application of radio spectroscopy methods.

In the process of electric and heat energy production based on the fuel burning, the energy efficiency and the ecological compatibility of the process essentially depend on the mode and operability of the burning system. The presence of excess concentration of nitric, carbon and sulfur oxides, benzopirren and other harmful admixtures in the effluent gas indicates nonoptimal operation of equipment and leads to environment pollution. Since there are no simple and reliable admixture inspection devices, based on traditional methods of inspection, it is impossible to fulfill the dispatching control of the burning modes.

In the offered project the radio spectroscopy approach based on resonant interaction between electromagnetic field and gaseous mediums is used. Since to each gas corresponds its own resonant absorption frequency (determined in micowave radio range), we can determine the concentration of particular gases probing the effluent gas. This system of radio spectroscopic investigation of effluent gases is a high-speed system and can perform automatic dispatching control of the burning modes.

Applications of acoustic electronics in power engineering

Investigations being conducted in MPEI on the wireless piezo-sensors for power engineering are very promising. These sensors are based on the use of surface acoustic waves.

The operating principle of acoustic-electronic sensors is based on the fact that external factors cause static deformations, which may be considered as parametric variation in elastic medium and the acoustic-electronic sensors geometry itself for acoustical waves of small amplitude. Variations in parameters and geometry cause variations in elastic (acoustic) wave velocity, which can be measured. Such sensors are already used in various equipment for pressure and mechanical deformation measurements.

On the basis of the principles described above, sensors of rotational moment for shafts of equipment for a wide variety of applications are produced [15]. Similar sensors are widely used in industrial equipment including power engineering equipment.

The sensors of electric and magnetic fields intensity are of interest for electrical power engineering. Owing to piezo-effect, the external electric field causes internal mechanical stresses in the acoustic duct, which leads to variation in acoustic wave velocity.

Remote surface acoustic waves sensors are used for continuous inspection of temperature of lightning arresters on transformer stations in the electric supply networks of high voltage. The pair of such sensors is located on the arrester and registering equipment is mounted in the distance of several meters from the arrester.

Power source charge/discharge automatic control

While developing modern autonomous power sources, electrochemical generators, energy accumulators for hydrogen power engineering devices, it is necessary to take into consideration that a series of electric parameters must be controlled and variety of contradictory factors must be allowed for, in order to maintain optimal and safe operating mode of charge and discharge. In this respect, the modern microelectronics and micromechanics achievements, new measuring sensors and micro-controllers with different channels of data transmission open qualitatively new opportunities for parameter measurement (with interference filtering) and application of optimal control theory algorithms and precise regulation with minimal transients, possibilities of remote control and event history saving. Thus, in cooperation with chemical experts the MITEK device has been developed. The device generates current of 1—100 A in the electrochemical cell with possibility of accurate measurement of polarization curves and optimal current maintenance in the electrochemical cell. This device was highly appreciated by experts and was more than once demonstrated at international exhibitions.

Resume

Evidently, it is impossible to describe all projects and ideas offered for development in one short paper. But even the developments described above prove the huge potential of modern wireless engineering and achievements of radio electronics in the fuel-energy complex.

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Гречихин В. А., Замолодчиков В. Н., Смольский С. М. **Применение беспроводных систем мониторинга и связи в энергетике.**

Ключевые слова: радиосвязь, беспроводные датчики, РЛС ближнего действия, лазерные измерительные системы, радиотермография, радиоспектрометрия, акустические датчики.

Описаны некоторые достижения современной радиоэлектроники, которые свидетельствуют о громадном потенциале современной беспроводной техники и достижений радиоэлектроники для использования в топливно-энергетическом комплексе. Рассмотрены беспроводные корпоративные системы связи, вопросы применения на энергетических объектах измерительных систем ближней радиолокации, перспективы использования лазерных измерительных систем, методы радиотермографии и радиоспектроскопии, возможности беспроводных акустоэлектроных датчиков.

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Гречихин В. А., Замолодчіков В. Н., Смольський С. М. **Застосування бездротових систем моніторингу та зв'язку в енергетиці.**

Ключові слова: радіозв'язок, бездротові датчики, РЛС ближньої дії, лазерні вимірювальні системи, радіотермографія, радіоспектрометрія, акустичні датчики.

Описано деякі досягнення сучасної радіоелектроніки, які свідчать про величезний потенціал сучасної бездротової техніки та досягнень радіоелектроніки для використання у паливно-енергетичному комплексі. Розглянуто бездротові корпоративні системи зв'язку, питання застосування на енергетичних об'єктах вимірювальних систем ближньої радіолокації, перспективи використання лазерних вимірювальних систем, методи радіотермографії та радіоспектроскопії, можливості бездротових акустоелектронних датчиків.

Росія, Москва, Національний дослідницький університет "Московський енергетичний інститут".

НОВЫЕ КНИГИ

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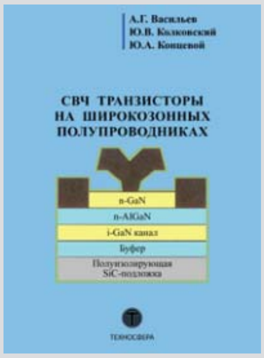
Васильев А. Г. и др. СВЧ-транзисторы на широкозонных полупроводниках.— Москва: Техносфера, 2011.— 456 с.



Книга представляет собой учебное пособие по физическим основам и технологии создания транзисторов на широкозонных полупроводниках. Рассмотрены свойства двумерного электронного газа и физика гетеропереходов, в основном типа AlGaN/GaN. Дан обзор структур транзисторов на основе широкозонного полупроводника GaN. Рассмотрены структуры транзисторов на алмазе и карбиде кремния. Рассмотрены свойства подложек из сапфира, карбида кремния и других материалов, применяющихся для создания гетероструктур. Детально проанализированы методы изготовления гетеропереходов при использовании эпитаксии из металлоорганических соединений и молекулярно-лучевой эпитаксии. Рассмотрены требования к омическим контактам и барьерам Шоттки, при использовании которых создаются гетероэпитаксиальные полевые транзисторы с высокой подвижностью электронов в канале (HEMT). Рассмотрена технология транзисторов на алмазе. Дан детальный обзор методов контроля технологических процессов, применяющихся при изготовлении транзисторов. Рассмотрены методы измерения основных параметров СВЧ-транзисторов и методы контроля надежности транзисторов. Книга предназначена для студентов, обучающихся по профилю «Электроника и наноэлектроника». Книга будет полезна также магистрам, аспирантам, инженерам и научным работникам, специализирующимся в области разработки и применения изделий твердотельной электроники.