Pulse and Synchro-Photon Electronics

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By

Ferdinandas Vaitiekūnas

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ANNOTATION

The theory of pulsed processes in transistors, diodes and injection lasers capable of operating at ultrahigh frequencies in a large-signal mode is presented in this book. Video pulses with a pulse repetition rate from hundreds of MHz to 1, 2 and 4 GHz were obtained from models of generators. During the electrical switching of an element, its irradiation with photon pulses significantly increases the response speed—this is synchrophotons electronics. Differences between microwave electronics and pulse electronics are also outlined. The methods for developing electronics up to quantum computing devices are shown.

The book is intended for graduate students in electronics, radiophysics and engineering—developers of active elements and for measuring pulse generators with a low or gigahertz pulse repetition rate.

FOREWORD

The progress made by society and its infrastructure has led to the wide application of digital electronic systems that process large arrays of information. Data are transmitted over short and long distances. The necessity for a parameter that characterizes the efficiency of the operation of pulsed and digital devices or a whole system in a time domain has arisen. This would be the operating speed parameter of electronic digital equipment which operates in pulse mode. Any system consists of active elements, and therefore the operating capability of the system depends on the impulse and frequency response characteristics of semiconductor electronics–transistors, diodes, light emitters, etc., operating in waveguide-fibre systems.

In many scientific publications in the field of electronics and radiophysics, the parameters of certain types of elements are considered. However, the interest from a unified standpoint in evaluating the processes of fast carrier transfer in elements of different types of electronic elements has matured. This will allow a comparative assessment of the performance of electronic elements at superhigh frequencies.

Pulse processes at superhigh frequencies in active elements of various types were investigated in the Scientific Laboratory of Impulse Processes at the Faculty of Physics of Vilnius University. The work started with a selection of semiconductor elements capable of operating in the nonlinear mode of a large signal at superhigh frequencies. Rigorous mathematical methods of calculation are adapted for the analysis of processes in the time domain, and a simulation of impulse and frequency processes in semiconductor structures with different physical mechanisms has been carried out. The analysis is based on the impulse process, which covers the transfer of carriers through the structure of the element in all stages of the formation of the impulse signal. This technique made it possible to compare the impulse characteristics of the elements. The models of generators or pulse shapers based on the selected elements were developed and the processes occurring in them at low and gigahertz frequencies were experimentally investigated.

The monograph presents studies of pulsed sub-nano and picosecond processes in bipolar and unipolar transistors, avalanche transit and tunnelling diodes, structures with superlattices and emitters based on hetero junctions operating in different modes of generation or formation of pulses at gigahertz frequencies. Methods for calculating the parameters of the generated pulse signals, which can be applied in engineering practice, are presented. The simulation of the processes made it possible to distinguish an exemplary impulse element—a transistor with a permeable base. The effect of the charge carrier spreading to the edges of the transfer channel is absent in this type of transistor. The unification of the disciplines of physics of semiconductor electronics, optoelectronics, radiophysics and electrodynamics into one subject with the theory of pico-femtosecond processes of carrier transfer has formed the basis for a separate area of research in synchro-photons electronics. Therefore, it has been pointed out that the ways to increase the speed of electronics at low and superhigh frequencies are different.

The original structures of semiconductor active electrical and optical elements, methods of their metrology and methods of generating pulses at superhigh frequencies have been proposed and patented. These elements and the above-mentioned modelling as an aggregate, have revealed fundamental differences from microwave electronics and determined the content of the subject—pulse electronics. It covers various physical disciplines such as semiconductor electronics and optoelectronics, radiophysics, long transmission lines and electrodynamics.

An introduction to the specific topic of pulse electronics at superhigh frequencies is presented in the first chapter of the book. Methods for analyzing electrical and optical pulse processes in semiconductor structures and waveguides including their possible irregularities are briefly outlined. This peculiarity of coaxial, trough and strip lines causes a distortion of the shape and parameters of the transferred pulse signals.

From Chapter 2 to Chapter 5, the results of the study of bipolar and unipolar transistors and diodes are considered. Chapters 6 and 7 are devoted to heterojunction lasers, followed by synchro-photons electronics in Chapter 8, and pulse electronics with the prospect of its development into the quantum transistor, a microcircuit and a computer that works with qubits are discussed in Chapter 9.

The generality of the principles essential to the development of pulse signal shapers or generators and digital electronic devices has led to a unified consideration of the processes of pulse switching of the various elements of semiconductor electronics.

To contribute to the academic practice of work with a new generation of active elements, there was constant cooperation with the developers of avalanche-transit diodes from the ERA Association, heterojunction lasers at the POLYUS Research Institute by M. F. Stelmakh and cluster superlattices at the Ioffe Institute of Physics and Technology. Seminars were held and the presentation of results of complex research and specific solutions were proposed for the implementation of elements in new developments. This has led to a significant improvement in the pulse-frequency properties and parameters of the elements of pulse electronics. Such elements are used in the development of measuring pulse generators at the Vilnius Scientific Research & Development Institute of Radio Measurement Instruments. Measurement generators of a new generation with a pulse repetition rate of 1-2GHz, generators of optical pulses and reflectometers have been developed.

Electronic and optoelectronic devices are operating at gigahertz frequencies. Information systems with gigabit data rates have been widely mastered. For the operation of such systems, appropriate ultrafast metrological support is required. It is based on measuring pulse generators. They are classified as electrical and optical, and also differ in the pulse repetition rate at low and superhigh frequencies. The presence of impulse metrology creates the basis for further improvement and development of information systems.

The author is deeply grateful to his colleagues—the physicists Česlovas Pavasaris, Juozas Vyšniauskas, Valerijonas Žalkauskas, Kęstutis Sutkus, Gintautas Šimėnas, Sigitas Kuršelis, the mathematician Gėlytė Kazakevičienė and engineer Eugenijus Bugaec for the joint long-term scientific work and original developments of knowledge in electronics.

The material presented in the monograph was discussed at seminars at the Faculty of Physics of Vilnius University and the Lobachevsky State University of Nizhniy Novgorod. Also, the research topics were presented to eminent scientists working in the scientific fields of radiophysics, semiconductor physics, electronics and optoelectronics. For their discussions, valuable advice and remarks, the author sincerely thanks the doctors of physical and mathematical sciences, professors and academician at the Russian Academy of Sciences: S. A. Nikitov (Kotelnikov Institute of Radio Engineering and Electronics RAS, Moscow), V. I. Esipenko (Nizhny Novgorod State Technical University named after R. E. Alekseev) and D. O. Filatov (Lobachevsky State University of Nizhny Novgorod).

I am also deeply thankful to Doctor of Technical Sciences, V. P. Duraev and his colleagues at the Research Institute POLYUS, now the scientific and technical firm NOLATECH (New laser technology, Moscow), Doctor of Technical Sciences M. Yu. Filatov (ERA Association, now the Design Bureau OPTRON, Moscow) and a leading specialist in the development of measuring pulse generators and the chief designer for pulse metrology equipment, including fibre-optic communications (Institute of Measuring Instruments, Vilnius) for multiple discussions on the research work and many years of ongoing support.

The benevolent support of the Dean of the Faculty of Physics of Vilnius University, Professor Viktoras Kybartas, who is sadly deceased, is remembered with deep gratitude.

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—The Author

CHAPTER 1

INTRODUCTION TO ELECTRONICS AND PULSE RADIOPHYSICS

List of symbols and notations

β	current gain;
NRZ	Non-Return to Zero;
RZ	Return to Zero;
f_{osc}	frequency of the oscillation;
$K(\omega, A)$	transmission factor of the amplifier without the feedback;
$\beta(\omega)$	the function of the transmission factor on the feedback circuit;
A	signal amplitude;
$\mathcal{E}_{\mathrm{C}}$	conduction band bottom energy;
$\mathcal{E}_{\mathrm{g}}$	bandgap;
$\mathcal{E}_{\mathrm{F}}$	Fermi energy level;
$\mathcal{E}_{\mathrm{D}}$	donor energy level;
$\mathcal{E}_{\mathrm{A}}$	acceptor energy level;
T_{C}	critical temperature of a material;
T_{op}	maximal operating temperature of the device;
e	electron charge;
D_n	electron diffusion coefficient;
L	diffusion length;
τ_n	electron lifetime;
L_n	electron diffusion length;
m^*	effective mass;
$\hbar^2$	Dirac constant;
ε_n	electron energy;
k	wave vector;
j	current density of semiconductor electronic element;
G	carrier generation rate;
R	carrier recombination rate;

τ	carrier lifetime;
G_0	carrier generation rate under the thermodynamic equilibrium;
R_0	carrier recombination rate under the thermodynamic equilibrium;
$f_{\mathrm{F}p}$	Fermi function for the holes;
E_{diff}	diffusion electrical field;
U_{f}	forward bias voltage;
U_{r}	reverse bias voltage;
$e\varphi_{\mathrm{cont}}$	height of the potential barrier;
p_{n0}	the density of minority charge carrier holes in *n*-type semiconductor;
n_{p0}	the density of minority charge carrier electrons in *p*-type semiconductor;
np	the equilibrium concentration of minority charge carriers;
N_n	doping levels of the *n* region;
N_p	doping levels of the *p* region;
J	the density of forward current of conductivity electrons;
C_{b}	barrier capacitance;
$\mathrm{d}Q$	charge in the *pn* junction;
$\mathrm{d}U$	variation of potential difference in the junction;
l_{B0}	thickness of the technological base;
α	coefficient related to the base current gain coefficient β;
α_0	coefficient value at low frequencies;
ω_α	frequency at which α decreases by 3 dB;
f_{c}	cutoff frequency;
$f_{\mathrm{c\ commE}}$	cutoff frequency in the common emitter connection;
$f_{\mathrm{c\ commB}}$	cutoff frequency in the common base connection;
$fmax$	the maximum frequency of generation;
τ_{C}	time constant of the feedback circuit;
f_{T}	transition frequency;
β	current gain coefficient;
C_{d}	diffusion capacitance;
$\mathcal{E}_{\mathrm{g}}$	band gap of semiconductor device;
Φ	work function of the output which is estimated by energy needed to transfer an electron from a semiconductor crystal to the vacuum;
Q	quantum well bottom energy level;
S	quantum well width;
$\hbar$	Planck constant;

W	particle energy;
L_{depl}	thickness of the depletion layer;
L_{sd}	source-drain length;
I_{sat}	saturation current;
N_{21}	number of transitions in the active area with stimulated radiation;
N_{12}	number of photon absorption events;
B	Einstein coefficient;
ϑ	density of the radiation at ν_{21} frequency field;
η	coefficient of the linear absorption by inactive centres;
k_0	initial gain;
α	parameter of the active medium that reflects nonlinearity for ν_{21} frequency;
$\Delta\vartheta$	increase of the radiation density;
r_1, r_2	reflection coefficients of the resonator facet mirrors;
t_{pp}	duration of the pulse process;
φ	gradient of the electrostatic potential;
D	diffusion transfer of the carriers which are created in the presence of the gradient of their density;
$v_{n,p}$	velocity of charge transport;
i	mesh-current;
t_{est}	transient process establishment time;
I_0	bias current of the laser;
$I_{\sim}$	amplitude of the modulating sinusoidal current;
d	width of the active region;
τ_e	lifetime of the minor charge carriers in the laser active region;
τ_{ph}	photon lifetime in the laser resonator;
G	integral gain;
i_0	normalised laser injection current;
α	factor of the spontaneous radiation;
ΔN_0	largest possible difference in the populations created by the pumping (unsaturated population difference);
$\tau_{21}w$	
k_{sw}	voltage standing-wave ratio (VSWR);
R_L	transmission line load resistance;
ρ	characteristic impedance of transmission line;
U_{inc}	incident voltage wave amplitude;
t_{pr}	forward propagation time;
t_{imp}	pulse duration;
U_{in}	pulse amplitude;

I_{inc}	incident current wave amplitude;
λ	wavelength;
λ_{cr}	critical wavelength of a signal;
ε	dielectric constant;
t_{d}	signal delay time in transmission line;
μ	magnetic permeability;
v	wave propagation velocity;
k_λ	velocity factor of wave propagation;
l_{ext}	external wave travelling path in bent waveguide;
l_{int}	internal wave travelling path in bent waveguide;
φ_{ext}	external wave phase in bent waveguide;
φ_{int}	internal wave phase in bent waveguide;
k_{ir}	coefficient of irregularity for bent waveguide;
L_{c}	geometric length of the central coil of the spiral waveguide;
f_{hh}	frequency of the higher harmonics;
$\Delta L_{\mathrm{ex,in}}$	difference of the external (L_{ex}) and the internal (L_{in}) spiral branches of the spiral waveguide;
$l_{\mathrm{ex}n}$	length of external line of a waveguide;
$l_{\mathrm{in}n}$	length of internal line of a waveguide;
s	ratio of the incomplete spiral waveguide segment to the last full turn;
l_{n}	length of the spiral of n^{th} turns in spiral waveguide;
$\varepsilon_{\mathrm{ext}}$	dielectric permittivity at the external boundary of spiral waveguide;
$\varepsilon_{\mathrm{in}}$	dielectric permittivity at the internal boundary of spiral waveguide;
ρ_{trough}	characteristic impedance of the trough line;
R_0	radius of the first turn of the spiral trough line;
$\alpha = \omega / v$	phase constant of the wave in spiral line;
P_Σ	radiation power.

The operating speed of the active semiconductor elements is one of the most relevant problems in the development of the scientific direction of electronics and photo electronics. This is due to the development of computing devices, communication facilities and metrology instruments operating at gigahertz frequencies. Elements of pulse electronics are an integral part of the waveguide and transmission cable systems. The generated impulse signals have specific parameters in time, frequency and amplitude or power. In this chapter, certain issues of semiconductors, mechanisms of electronics and superhigh frequency radio physics are reviewed which are closely related to the possibility of achieving a minimum duration of the transient process or impulse operation of electronics at superhigh frequencies. These features of semiconductor electronics create a fundamental difference between the methods of generating video pulses and generating sinusoidal oscillations. The development of high-speed pulse systems is based on the pulse process in electronic systems operating in waveguide transmission lines for transverse electromagnetic waves. The merging of electronic and optoelectronic systems to generate pulsed electrical or optical signals has become an independent task. The successful solution for the scientific direction under consideration essentially depends on the development of its theory, methods of analysis and experimental developments.

1.1 Sinusoidal and pulsed signals

Electronics, as fundamental science, has certain thematic areas. One of them is microwave electronics. The operation of most microwave electronic devices is based on the mechanisms of the interaction of electrons with electromagnetic fields at superhigh frequencies. The dominant devices are vacuum and solid-state devices that are capable of generating, amplifying and transforming oscillations at superhigh frequencies. The systems of such electronics are based on the integration of an electronic device with electrodynamic systems (resonators, wave propagation delay and waveguide systems). Sinusoidal oscillations are coupled in the form of electromagnetic waves from microwave electronic devices and these oscillations propagate through the metal waveguides working at a centimetre or millimetre wavelength range. These waves are radiated by antennas and they propagate in free space and travel long distances.

Over the past decades, a new field in electronics, which has laid the foundation for the development and wide application of digital information and communications systems based on optical fibres, has formed. It includes the theory of pulsed processes in semiconductor electronic and optoelectronic structures operating at superhigh frequencies. The generation of electrical or optical pulsed oscillation with pico-, and femtosecond time parameters is realised by special ultra-wideband circuit devices and the generated signals are transmitted by the coaxial waveguides or optical fibres. The measurement of such pulsed processes and their parameters is also specific. The totality of the mentioned topics proposed the need to solve a large number of physical, technical and technological problems. This led to a necessity to separate this field of knowledge (with its inherent devices and methods of oscillation generation, as well as measurements) into a separate scientific direction called pulse electronics [1].

Electrical and optical impulse oscillations can be encoded, which turns them into information signals. Every system for processing and transmission of such signals should ensure minimal handling time and strictly maintain the information contained in the signal. Therefore, the solving of complex problems requires information systems with a high or maximum possible operating speed. For these purposes, semiconductor electronics and optoelectronics that operate at super high (gigahertz) frequencies are implemented in the waveguide systems of distributed parameters.

In the coming years, one of the biggest changes in the system operation speed and performance is expected [2]. The 5G network will operate at a significantly higher transmission and signal processing speed. Now mobile communication systems operate below 6 GHz. One of the first public tests of the 5G system showed 10 Gbit/s operations at a frequency up to 73 GHz [48]. Electronic components should be able to outperform the operation of today's devices. New technologies in the microwave range will enable a significant enhancement in the application capabilities that were previously used for military and space applications. Pulse electronics, a relevant and active development in this field, is being observed.

The operation of electronics is based on the generation and processing of electromagnetic oscillations as well as on obtaining the signals with embedded information. This operation is characterised by a number of parameters and features which determine possible applications. The first difference between sinusoidal and pulsed signals is their shape. The spectral functions of such signals also significantly differ; they determine the frequency characteristics of the corresponding devices of microwave electronics and pulse electronics (Fig. 1.1) [3].

Digital coding is widely used. Text, figures and any other information in the binary system are represented in the form of numerical codes. One byte consists of eight digits—bits, in each of which one value can be stored: 0 or 1. Depending on the protocol, zero voltage can carry a value of 0 or 1 (as well as voltage pulse ($+U$)). Representing 0 and 1 by one bit means all characters of the Latin alphabet can be expressed by one byte. Two bytes are used for the digital representation of Chinese characters. Two bytes are equal to 16 bits or 2^{16}. This covers 65,536 different integer values. Two conjoined bytes are called a word. The information representation by bytes puts forward another issue of electronics operations: oscillation modulation is replaced by digital coding. There are various methods of such coding. The simplest of them are Non-Return to Zero (NRZ) and Return to Zero (RZ) (Fig. 1.2).

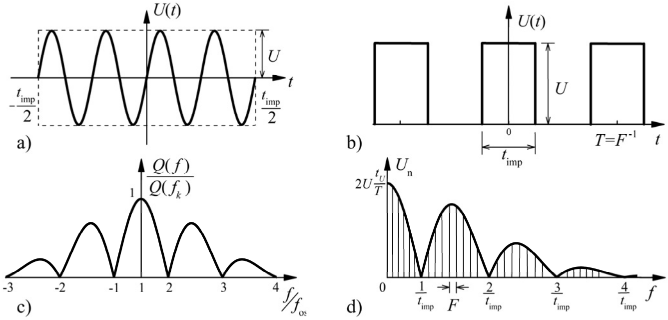

Fig. 1.1 Radio pulse (a) and video pulse (b) oscillations and their spectrums (c and d, respectively) (U is oscillation amplitude, t_{imp} is impulse duration, T is period and F is pulse repetition rate, Q is the normalised modulus of the spectral density of the radio pulse, f and f_{osc} are frequencies of harmonics).

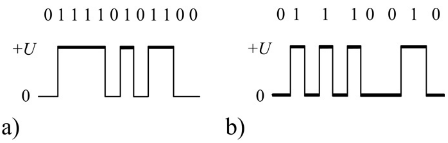

Fig. 1.2 Digital coding of information signal: (a) NRZ, (b) RZ.

1.2 Generation of electrical oscillations

A large number of different methods of generation, signal autogenerators and shapers of impulses are known. Autogenerators are based on positive feedback, which serves for the excitation of the active electronic element and maintaining the generation of the electrical oscillation. Despite the large variety of such devices, they are divided into two groups: generators of harmonic (sinusoidal) and generators of pulsed (non-sinusoidal) oscillations [3]. The latter are relaxation generators that generate pulses of various shapes: rectangular, trapezoidal, triangular, sawtooth, exponential and bell-shaped [48].

Generators of harmonic oscillations. Generators of the first type have an oscillatory system (Fig. 1.3). At low and medium frequencies it is an oscillatory circuit comprised of lumped inductance (L) and capacitance (C). Voltage fluctuation through the feedback circuit is fed into the nonlinear element, where it is amplified. The sinusoidal oscillation is generated at the resonant frequency of the circuit. The frequency of the oscillation is determined by the circuit parameters: $f_{\mathrm{osc}} = 1/(2\pi\sqrt{LC})$. At superhigh frequencies, microwave electronics operate in a system with a cavity resonator (resonant circuit), which consists of the waveguide segments.

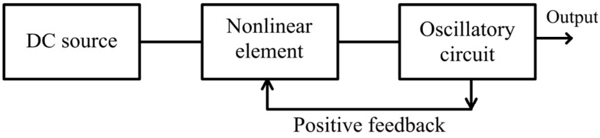

Fig. 1.3 Diagram of the autogenerator of harmonic oscillation.

Generators of relaxation pulsed oscillations. The operation of the relaxation oscillation generator is based on charging and discharging the capacitance through the nonlinear conductivity of an active element. There are no resonant elements in the oscillatory circuit. One or more elements of such generators operate in the key mode: on/off. Three operation modes are characteristic of the generator: auto-oscillation mode, standby mode with the external trigger or synchronisation.

A diagram of the generator of relaxation oscillation is presented in Fig. 1.4. One or two nonlinear elements are connected into a circuit of blocking oscillator, multivibrator or trigger, alternately switching the current of the capacitance to charge or discharge it. The positive feedback circuit controls the switching of the nonlinear elements. The capacitance recharging time determines the switching frequency (F) and the period (T) of the generated pulsed oscillation.

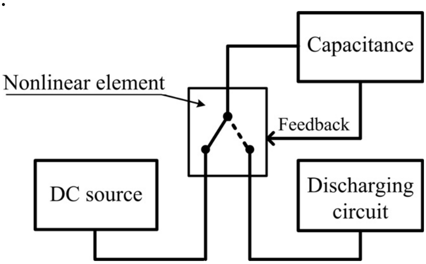

Fig. 1.4 Diagram of the autogenerator of relaxation oscillations.

During the self-excitation phase of autogenerator operation, the oscillation amplitude (A) increases from zero to its stationary value (A_{st}). The condition of the stationary self-oscillation with constant amplitude is expressed by the following:

$$K(\omega, A)\beta(\omega)\exp\left(j(\varphi_{\Sigma} + \varphi_{\beta})\right) = 1, \tag{1.1}$$

where $K(\omega, A)$ is the transmission factor of the amplifier without the feedback, $\beta(\omega)$ is the function of the transmission factor of the feedback circuit, and A is signal amplitude.

In order to have stable self-oscillation with constant stationary amplitude, the energy lost in the feedback circuit must be restored by the amplifier. This condition requires keeping a balance of amplitudes:

$$K(\omega,\ A_{\mathrm{st}})\beta(\omega) = 1. \tag{1.2}$$

The condition of the phase balance has to be fulfilled as well. Therefore, the positive feedback, which serves to trigger the voltage fed into the nonlinear element at appropriate times with the appropriate phase, is necessary for generating:

$$\varphi_{\beta}(\omega) + \varphi_{\mathrm{k}}(\omega) = 2\pi n, n = 1,2,3, \ldots \tag{1.3}$$

If the amplitude and phase balances are obtained at the same frequency, then a single frequency, i.e., single harmonic oscillation is excited in the generator. The oscillatory circuit guarantees that the frequency shift at frequency ω_0 is 180^0 ($\varphi_{\mathrm{c}}(\omega_0) = \pi$), and the condition of amplitude and phase balance is satisfied only at this frequency. The parameters of the oscillatory circuit determine the frequency of the harmonic oscillation that is generated:

$$\omega_0 = \frac{1}{\sqrt{L_{\mathrm{c}}C_{\mathrm{c}}}} \tag{1.4}$$

If the amplitude and phase balance are obtained simultaneously for the frequency spectrum band, oscillation consisting of a corresponding number of harmonics is generated. A combination of these harmonics creates the pulse shape of oscillation. Signals close to the rectangular shape are composed of a large number of harmonics. The pulse rate of pulses generated by the relaxation generator is determined by the time constant of energy accumulation (RC) and by the parameters of the feedback circuit. The minimal value of it is in the microsecond or fraction of the microsecond range. Therefore, the pulse repetition rate does not exceed tens of megahertz. The nonlinear oscillation theory is used for describing such systems.

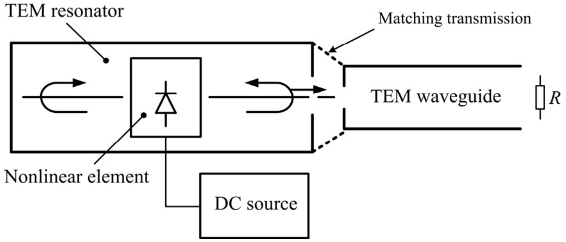

Fig. 1.5 Diagram of the pulse autogenerator based on the TRAPATT diode.

Investigations of impulse electronics have created the possibility of generating pulses with gigahertz range pulse repetition rates. Figs. 1.5 and 1.6 show diagrams of pulse generators. The TRAPATT diode of the autogenerator is placed in the coaxial resonator (Fig. 1.5). The generated pulsed oscillation is transmitted through a matching transition into a coaxial waveguide.

Pulse shapers. The generators with external triggering (Fig. 1.6) can be based on different impulse electronic elements: bipolar and field-effect transistors, charge-storage diodes, semiconductor emitters and devices operating with a synchro-photon effect. An element of impulse electronics is placed in the waveguide for transverse TEM waves. It is triggered by the sinusoidal or pulse signal from the external generator. When generating electrical or optical unit steps, the pulse repetition rate can be low. At superhigh frequencies, the maximum pulse repetition rate is determined by the physically realisable minimum duration of the pulsed process in the electronic element.

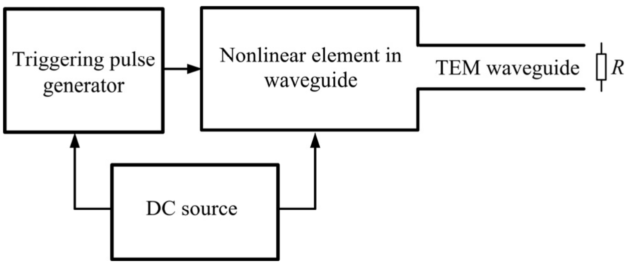

Fig. 1.6 Diagram of the pulse generator with external triggering.

The pulsed oscillation shaping process occurs in the structure of a semiconductor device. The time and frequency parameters of oscillation are determined by the impulse characteristics of the device, its operation mode and the properties of the waveguide system. The output of the generators with semiconductor emitters is connected to the optical fibre.

1.3 Semiconductor materials

Semiconductors. Semiconducting according to conductivity is between the conductors (metals) and dielectric materials. The main material of semiconductor electronics is monocrystalline tetravalent silicon (Si). Germanium (Ge), gallium arsenide (GaAs) and compounds of III-V groups of the periodic table (InAs, GaSb, InP, GaAlAs, etc.) are also used. Monocrystals are doped to achieve the required conductivity and magnitude of the flowing current. When the atoms of a pentavalent element (phosphorus P, arsenic As) are introduced into silicon, the atoms of the crystal lattice of the main materials are replaced by the impurity atoms (donors). Four of the five electrons of an impurity atom form covalent bonds with the four neighbouring atoms of the main semiconductor material. The fifth electron is excess and it becomes free (Fig. 1.7). Less energy is needed to separate it from the impurity atom.

To obtain hole conduction, silicon is doped with trivalent (acceptor) impurities (e. g., boron B). Each impurity atom forms a covalent bond with three neighbouring silicon atoms. For the fourth bond with a silicon atom, a boron atom lacks one valence electron. The boron atom captures an electron from the covalent bond of a neighbouring silicon atom and becomes a negatively charged ion (Fig. 1.7). The silicon atom which loses an electron creates a hole.

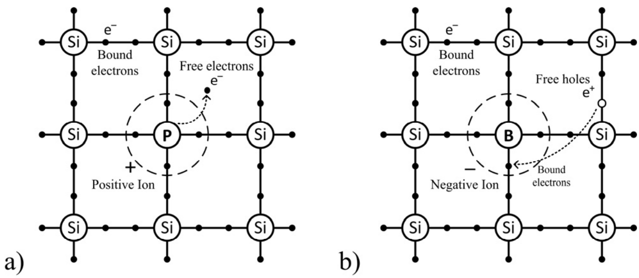

Fig. 1.7 Semiconductor with a pentavalent donor (*n*-type) impurity has free electrons (a), trivalent acceptor (*p*-type) impurity creates holes (b).

The physical states and processes in semiconductors are presented by energy diagrams in Fig. 1.8. [5, 6]. In the upper part of the diagram, there is a conduction band and its bottom energy is $\mathcal{E}_C$. These two bands are separated by a $\mathcal{E}_g$ width band gap. Electrons cannot have the energy of this band; therefore, it is called the forbidden band. The band gap value in semiconductors is measured by electronvolts. At the bottom of the diagram, the valence band $\mathcal{E}_V$ is shown. It is the band of allowed electron states in the solid body, and it is filled with valence electrons. The top of the valence band is limited by the energy $\mathcal{E}_V$. At absolute zero temperature, all free electrons occupy the lowest energy levels, and there is no electrical conductivity in the crystal. In the middle of the band gap, there is the Fermi energy level $\mathcal{E}_F$. The Fermi level defines the maximum energy that a free electron of a conductor (metal) can have at absolute zero temperature $T = 0$ K. A semiconductor, the same as a dielectric, has zero conductivity at absolute zero temperature. Donor levels $\mathcal{E}_D$ are in the band gap close to the bottom of the conduction band, while acceptor levels $\mathcal{E}_A$ are near the top of the valence band. With temperature increase, electrons obtain sufficient energy (in the order of 0.01 eV) for ionisation (electron detaching from the impurity atom).

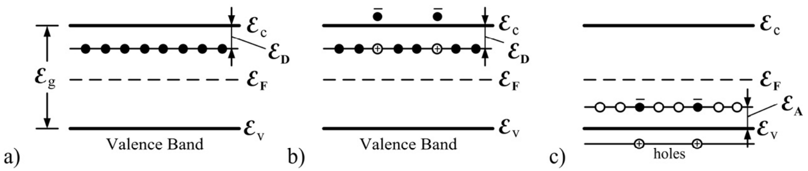

Fig. 1.8 Semiconductor energy diagrams: (a) semiconductor doped by donor impurities at absolute zero temperature, (b) semiconductor doped by donor impurities at a temperature above absolute zero, (c) semiconductor doped by acceptor impurities at a temperature above absolute zero.

Electrons become free and transfer to the conduction band. The acceptor impurity captures an electron from the crystal atom: a hole is formed. The presence of free electrons and holes creates the conductivity of the crystal.

Fig. 1.9 shows an energy diagram of an *n*-type semiconductor at temperature $T >> 0$ K. A lower energy is needed for an electron detaching from its atom in a donor doped crystal. At room temperature (300 K) donor atoms are completely ionised. The donor doped crystal has purely electronic conductivity, and electron density is equal to the density of donor impurities: n=N_D. In a typical electronic semiconductor, the inequality n>>p is valid (segment (2) in Fig. 1.9). A further temperature increase transfers electrons from the valence band to the conduction band and the semiconductor obtains the properties of a conductor (segment (3) in Fig. 1.9).

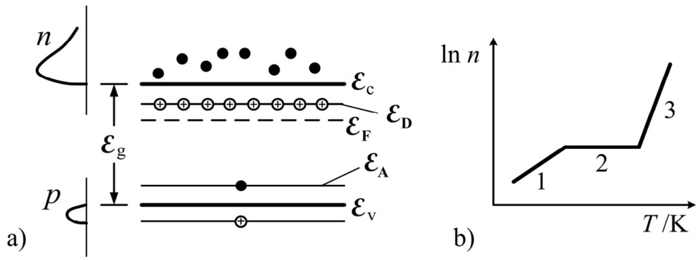

Fig. 1.9 Semiconductor with donor-type doping: at room temperature ($T = 300$ K) n-type conductivity is present (2), and temperature much higher than normal ($T >>$ 300 K) causes electron transfer to the conduction band (3).

The characteristics of semiconductor materials that determine many properties of devices are presented in Table 1.1. The band gap energy determines the critical temperature T_C of material and the maximum operating temperature T_{op} of the device, the permissible value of reverse voltage and the spectral range of optoelectronic devices. E.g., if the temperature of a germanium-based device is changed from -60 ^{0}C to +70 ^{0}C, the forward current increases twice and the reverse current grows three times. Germanium has an advantage in terms of carrier mobility, while silicon operating temperature is more acceptable. Due to this, in many cases silicon overcomes germanium. Gallium arsenide is ahead of both of these materials.

The carrier mobility characteristic for material is one of the main factors that determines the device operation speed and the maximum frequency. Materials exclusively with electronic conductivity are used in impulse electronics. By definition, carrier mobility is an average directional carrier drift velocity (v_d) in a 1 V/cm electrical field (E): $\mu = |v_d|/|E|$. Consequently, drift velocity is used to express the flowing current: $j = en\mu E$, where e is the electron charge. In pulse electronics, devices with electron conductivity are used exclusively.

Table 1.1 Characteristics of semiconductor materials and operation temperature of devices based on these materials.

No.	Characteristic	Material			
		Ge	Si	GaAs	InSb
1.	Band gap, $\mathcal{E}$, eV (at 300 K)	0.67	1.12	1.43	0.18
2.	Maximum operation temperature, ^{0}C ($N_D = 10^{16}$)	~90	~250	>250	<90
3.	Electron mobility, cm^2/Vs	3900	1450	10500	77000
4.	Hole mobility, cm^2/Vs	1900	480	430	700
5.	Diffusion coefficient of electrons, cm^2/s	98	37	220	2000
6.	Diffusion coefficient of holes, cm^2/s	47	12	11	18

A free electron can simultaneously drift and move chaotically due to thermal velocity. In this case, the total carrier velocity is larger, and when it reaches the thermal energy $(3/2)k_{\mathrm{B}}T$, the carriers are called hot. Here k is the Boltzmann constant. Drifting hot electrons interact with the vibrations of lattice atoms—phonons, impurity atoms and structural defects. They 'heat up' the lattice, which generates new higher energy optical phonons. This phenomenon leads to saturation of the electron velocity, and it ceases to depend on the electrical field strength: $v = \mu E = \text{const.}$

Uneven distribution (gradient) of the carrier density in a volume semiconductor causes carrier diffusion—a movement of charge carriers (electrons). The carrier density tends to equalise along the crystal. Electrons have a negative charge and diffuse in the opposite direction of the vector of the gradient of density. Therefore, the direction of the vector of the diffusive electron density has to coincide with the direction of the gradient of electron density. Any directional movement of the electrical particles with the same charge type is an electrical current. Thus, the gradient of electron density in the electrical field creates drift and diffusion current components. The total electron current density is expressed by:

$$j_n = j_{n\mathrm{drift}} + j_{n\mathrm{diff}} = qn\mu_n E + qD_n \frac{\mathrm{d}n}{\mathrm{d}x}, \tag{1.5}$$

where $D_n = \mu_n kT/q$ is the electron diffusion coefficient. Simultaneously with a diffusion of the non-equilibrium carriers, their recombination occurs. Carrier density decreases in the regions of excess carriers. It is evaluated in a crystal without an electrical field. The distance at which the excess carrier density decreases by e = 2.718 times due to homogeneous diffusion is called the diffusion length (L). Because of diffusion, the electron travels this distance during the electron lifetime (τ_n). Thus, the diffusion length is related to the electron lifetime: $L_n = \sqrt{D_n \tau_n}$.

Charge carrier diffusion can occur in a semiconductor that initially has uniform carrier distribution, i.e., there is no gradient of the carrier density. However, if there is a temperature gradient in the semiconductor, charge carriers (electrons) from the region of the higher temperature will occupy higher energy states in the conduction band. States of similar energy in the crystal part of lower temperatures are free from electrons. Therefore, electrons from the heated region diffuse to the colder parts of the crystal. It is necessary to discern the carrier diffusion length from the carrier-free path. The free path is defined as the average distance travelled by a carrier between the two successive scattering events. Electrons, protons, atoms, etc. combine the properties of both particles and waves. They are qualified as particles, but their motion is described by the Schrödinger wave equation.

The movement of the conduction electron in the periodic potential under the action of the external force F_c can be described as the motion of the free electron that is affected only by the force described by Newton's law, but with effective mass m^*. The effective mass differs from the free electron mass in a vacuum and can be positive or negative. Therefore, the electron acceleration in the crystal lattice can be directed not parallel, but antiparallel to the external force F_c. This difference reflects electron interaction with the lattice. The effective mass is described by the ratio:

$$m^* = \hbar^2 \frac{\mathrm{d}^2 \mathcal{E}_n}{\mathrm{d}k^2}, \tag{1.6}$$

where $\hbar^2$ is the Dirac constant, $\mathcal{E}_n$ is electron energy, and k is the wave vector.

The total current of the semiconductor electronic element (expressed by current density) consists of four components: drift and diffusion of both types (electrons and holes) of the carriers:

$$j = j_{n\mathrm{dr}} + j_{n\mathrm{diff}} + j_{p\mathrm{dr}} + j_{p\mathrm{diff}}. \tag{1.7}$$

Charge carrier generation in a semiconductor crystal is caused by a number of factors: the thermal chaotic vibration of the atoms of the crystal lattice (thermal generation), exposure to light radiation (light generation), x-ray or γ-ray radiation, etc. As a semiconductor crystal is always (at a temperature above absolute zero) under influence of at least one of these factors, the charge carrier generation occurs continuously. Simultaneously with charge carrier generation the reverse process—electron return from the conduction band to the valence band—occurs: the pair of a free electron and a hole disappears, and energy is released. This process is called charge carrier recombination. The recombination mechanisms are divided according to two main features: the type of the released energy and the type of electron transition between the conduction and valence bands.

The recombination, when an electron directly transfers from the conduction to the valence band, and the released energy is equal to or larger than the band gap energy, is called interband or band-to-band recombination (Fig. 1.10 (a)). If the electron is first captured by the localised centre and then passes to the valence band, trap-assisted recombination takes place (Fig. 1.10 (b)). Localised centres with energy in the band gap are called traps. One of the schemes of recombination of electron and hole pair considers the case when one of the charge carriers is free and the other is trapped in the localised centre. The recombination scheme when both recombining carriers—electron and hole—are trapped in different localised centres is called interimpurity recombination (Fig. 1.10 (c)).

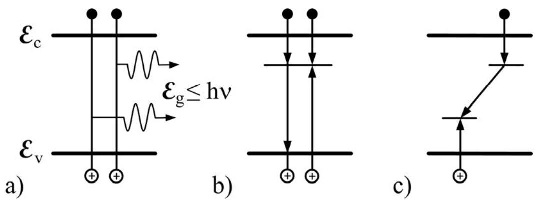

Fig. 1.10 Types of recombination: (a) radiative and nonradiative band-to-band recombination, (b) trap assisted recombination, and (c) interimpurity recombination.

Depending on the type of released energy, recombination can be radiative or nonradiative. During the radiative recombination, the released energy is a light quantum (photon) (Fig. 1.10 (a)). In the case of nonradiative recombination, the realised energy is transferred to the thermal lattice vibration (phonons) and no light is radiated. The energy can also be transmitted to the third carrier—a hole or an electron. And the energy is lost