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APPLICATION OF DIELECTRIC AND CONDUCTIVE EPITAXIAL FILMS IN SILICON TECHNOLOGY

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Abstract

In this paper the authors discuss a variety of solid-state electronic devices designed on the basis of different combinations of epitaxial layered dielectric and metal films in silicon technology that allows to create novel devices, including the devices operating on principles of quantum effects.

The paper reports Molecular Beam Epitaxy (MBE) technology for creating a new type of device. Intensive experimental research in the field of epitaxial growth of metals and dielectrics on surface of silicon and the study of their physical properties would most likely in the near future serve as a platform for the increased application of silicon devices that might displace other materials traditionally used in high frequency electronics (A_3 B_5, A_2 B_6), IR and UV - photo electronics.

Keywords

epitaxy, molecular beam epitaxy, epitaxial film, temperature, film, disilicide, thickness, intensity, heterostructures, heteroepitaxial layers.

Introduction

Recently, MBE-related technology has been widely used to engineer previously unknown semiconductor combinations and multilayer compositions based on layers of elementary (Si, Ge) and multicomponent (A^3B^5 and A^2B^6, their ternary and quaternary compounds) semiconductor materials.

This ensures positive boost in technical parameters of microelectronic devices, makes it possible to manufacture on a single substrate both silicon ICs and optoelectronic, detector and acoustic electronics devices embedded into ICs, thus expanding functionality of electronic devices.

Designing such structures will make it possible to manufacture on their basis a number of previously theoretically predicted integrated microelectronics devices, as well as a row of new devices. One of the promising solutions in this area is the silicon-on-dielectric (SOD) technology, which uses a layer on a dielectric (sapphire, SiO_2 Si_3N_4) substrate or an intermediate dielectric layer.

Use of SOD structures stemming in combination with design and technological peculiarities of integrated circuits (IC) provides effective solutions for improving key electro-physical and technical/economic parameters of modern CMOS ICs, including more efficient power consumption, speed, and radiation resistance functionalities.

Further research in this area is of greater importance due to the fact that at present there are a number of issues related to epitaxial growth technology and difficulties in understanding the physics of growth and detection of ionizing radiation based on epitaxial $CoSi_2$-CaF_2-Si hetero-structures. Their wider use will open up new opportunities for engineering devices with unique technological characteristics.

The development of molecular beam epitaxy (MBE) technology had allowed to engineer monolithic epitaxial hetero-structures that combine semiconductors, metals and dielectrics [1,2]. Such structures could serve as a basis for further implementation of new devices for microelectronics, functional electronics, and integrated optics. Currently, we have heard of experimental samples of transistors and integrated circuits formed on silicon $CoSi_2$-CaF_2-Si or NiS_2-CaF_2-Si, AlGaAs-Si, Si-GaF_2-Si hetero-structures [2]. There were also endeavors to create optoelectronic devices based on hetero-structures of A_3B_5 and A_2B_6 compounds on Si or CaF_2-Si surfaces [3].

The possibility of forming epitaxial dielectric and metallic films on silicon, as well as multilayer epitaxial structures with alternating layers of dielectric, semiconductor, and metal, creates the prerequisites for the creation of a number of new types of electronic devices.

Table 1. lists the materials that could be grown by epitaxial technique on silicon surface and on each other. The possibility of epitaxial growth of these materials on each other is made possible largely due to the closeness of their crystal lattice constants.

The technique of molecular beam epitaxy (MBE) allows growing various combinations of materials with a high perfection of crystal structure of films, with a low content of impurities and thicknesses in the range of 50 Å - 1 μm. The application of all materials in a single vacuum cycle makes it possible to engineer unique electronic devices based on various combinations of epitaxial layers of metal, dielectric and semiconductor.

Table 1

Material	Crystallogr phic group	Structure	$a(20C^0)$ Å	$б(20C^0)$ %	Physical roperties
Si	m 3m	алмаз	5,431	-	Semicon
CaF_2	m 3m	флюори	5,464	-0,61	ctor
$CoSi_2$	m 3m		5,365	+ 1,21	electric
		флюори			etal

a - lattice constant

b- lattice mismatch with silicon

Experimental

The paper describes various options for instrumental implementations of these epitaxial structures.

1. Silicon substrates with epitaxial layers of CaF_2 grown on their surfaces can serve as a basis for the subsequent growth of films of various semiconductor materials: silicon, germanium, A_3B_5, A_2B_6, A_4B_6, A_4B_6 -compounds. In this case, silicon substrates can serve as a universal basis for the epitaxial growth of a wide range of semiconductors. Compared to substrates based on other materials, silicon substrates have significant advantages, such as a large substrate size, high quality, and low cost, which makes them attractive for use not only in traditional silicon technology, but also as universal substrates for epitaxy of all major semiconductor materials.

In this area of application of epitaxial CaF_2/Si structures, one can highlight two important options. The first option relates to the "semiconductor on dielectric" technology, primarily, " silicon-on-dielectric" (SOD) technology. This technology is used in particular to eliminate the specific disadvantages of integrated circuits, in particular the “latch-up” effect of CMOS ICs. In addition, devices manufactured using this technology have increased radiation resistance. Finally, the possibility of alternate epitaxial growth of semiconductor and dielectric layers opens the way for the creation of three-dimensional integrated circuits.

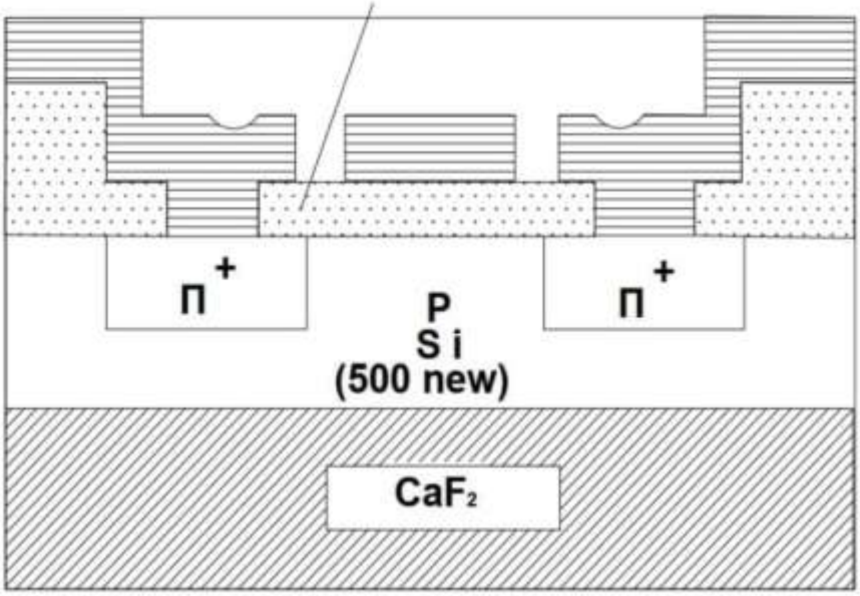
Configuration of MOS transistors designed by using the SOD technique КНД –$Si0_2$(110nm)

Another option is implementation of CaF_2/Si structures in the development of optoelectronic devices based on the A_2B_6 and A_4B_6 compounds, first of all, for the infrared range.

Currently, high-quality epitaxial Si/CaF_2/Si structures on Si substrates of different orientations have been obtained, and CMOS-IC samples have been fabricated on their basis [4]. When other semiconductors, such as Ge and GaAs are used as target substrates for epitaxy, high quality layers are obtained by applying various solid solutions based on alkaline earth fluorides (CaF_2, SrF2, BaF_2) as a dielectric layer. Rather promising results were obtained as a result of epitaxy of Ge and $CaSrF_2$/ i (III) [4]. GaAs layers grow by using epitaxy on both CaF_2/Si and BaF_2/CaF_2/Si.

For epitaxy of CdTe on a silicon substrate, a buffer layer consisting of BaF_2/CaF_2/ Si alternating epitaxial films is used [5].

Epitaxy of PdSe, PdTe, PdSeTe layers is carried out on BaF_2/(CaSr) F_2/CaF_2/Si buffer system. Infrared detectors are developed on the basis of such systems [5].



Si(100)

a

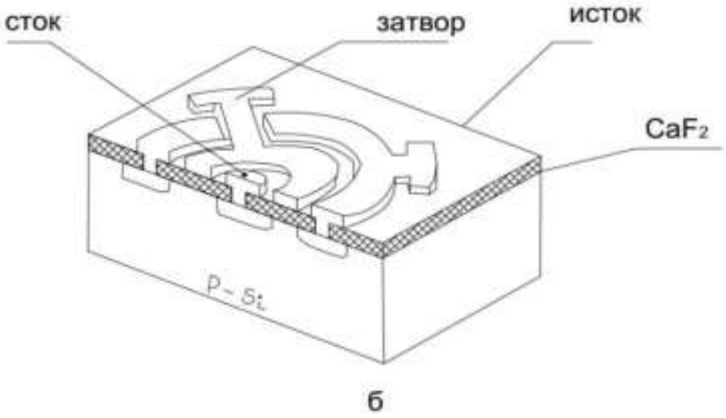


Fig. 1 Application of CaF_2 epitaxial layer in CMOS transistors:
a-MOS- structure engineered using SOD technology;
b-MOS transistor with CaF_2 as a gate dielectric material

Epitaxy of PdSe, PdTe, PdSeTe layers is carried out on BaF_2/(CaSr) F_2/CaF_2/Si buffer system. Infrared detectors are developed on the basis of such systems [5].

2. The structure "metal-epitaxial dielectric-silicon" can serve as a basis for the manufacture of MOS transistors with ultra-small thickness of the gate dielectric (Fig. 1b). The use of SiO_2 as a gate dielectric is limited to a minimum thickness of 20 nanometers. A thinner SiO_2 film contains holes and other defects. In addition, there is an inhomogeneity in SiO_2/Si interface, which reduces the carrier mobility in device structures. An MOS transistor based on the CaF_2/Si structure is devoid of such disadvantages due to the homogeneity and high crystal perfection of the CaF_2 dielectric film and the ordered CaF_2/Si interface.

The use in the above MOS structure along with epitaxial dielectric (CaF_2) layers of epitaxial metal ($CoSi_2$) layers makes it possible to implement an option of a 3-dimensional CMOS IC based on an epitaxial combination Si/CaF_2/$CoSi_2$/CaF_2/ Si.

3. One of the most promising areas of application of epitaxial films of cobalt silicide on silicon is the development of transistors with a metal and permeable base. Based on the Si_2/CoF_2/Si combination, it is possible to manufacture a silicon high frequency transistor with an operating frequency of up to 30 Hz [6]. In the case of a transistor with a metal base, it is necessary to form 50-100 Å thick epitaxial metal layer on a silicon substrate. In the course of manufacturing a transistor with a permeable base, holes with a size of about 20-200 nm are formed across the $CoSi_2$ layer.

To form a permeable base, it is necessary to implement the technique of submicron lithography, which complicates the technology of manufacturing transistors. In [7], an original method is proposed for engineering a permeable base in a $CoSi_2/Si$ structure with submicron-sized lines by conventional photolithography. The possibility of forming submicron holes regarding silicide due to specially selected growth conditions seems to be very promising [8]. The morphology of $CoSi_2$ film is very sensitive to the growth temperature, the ratio of silicon and cobalt fluxes during epitaxy, substrate orientation, etc. By varying growth parameters, one can change the size of holes in the film in a reproducible manner.

The key issue in the development of transistors with metal and permeable bases today is the growth of an epitaxial layer of silicon on the surface of the $CoSi_2$ film several thousand angstroms- thick with a high perfection of the crystal structure. Intensive research is currently being carried out in this direction, and the results received are very promising.

4. The multilayer $CoSi_2/Si/CoSi_2/Si$ …… $Si/CoSi_2$ structure (Fig. 2a) can be used to create a high frequency silicon avalanche-transit diode (ATD) [9]. Currently, the problem of designing high-power microwave diodes of millimeter and microwave range has not been solved. The output power of existing ATDs at frequency of 100 GHz does not exceed a few watts in a pulsed mode and tenths and hundredths of watt in a continuous mode. Combining avalanche-transit diodes into a series integrated structure based on a multilayer epitaxial structure with alternating semiconductor and metal layers can significantly increase the output power of ATD. This system represents a set of diodes connected in series, separated by layers of metal. Electrons and holes effectively recombine in the metal bulk within 10^{-17} seconds, due to which each diode can be considered as an isolated element while the device operates in the mode of generation of microwave oscillations.

Provided that the total length of the integrated device is much less than the wavelength, i.e. $L << c / f$, voltages on all elements have the same phase and, therefore, the total voltage on the device is equal to the simple sum of the voltages on the individual elements.

$CoSi_2$	n-Si	p-Si	$CoSi_2$	p-Si	n-Si	$CoSi_2$

Fig.2a. Epitaxial system «metal-silicon» as a basis for high power ATD.

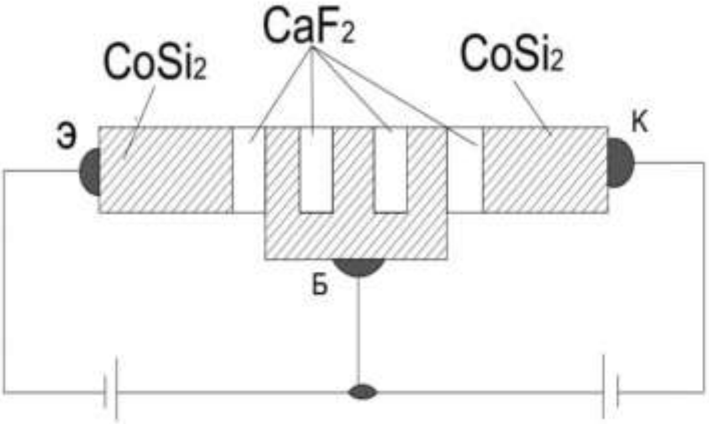


Fig.2b. Amplifying microwave device based on a metal-dielectric superlattice

Fig. 2. Devices based on multilayer epitaxial structures.

The total generated power of the integral series of ATD, consisting of *n* elements in *n* times greater than the power of microwave oscillations generated by a single element.

$P_{\sum} = n\, P_{\Delta \text{пd}}$

Due to the use of metal layers in the integral structure, which form a Schottky barrier with silicon, the system does not have the problem of injection of minority carriers, which reduces the reverse saturation current, as a result of which its efficiency increases. It is expected that this integrated version of the silicon ATD diode will operate efficiently at frequencies up to 300 GHz.

5. The $CoSi_2/CaF_2 \ldots CoSi_2/CaF_2/CoSi_2$ superlattice can serve as athe platform for creating a new amplifying device in the microwave range - the so-called tunnel resonant triode [10]. This device is schematically shown in Fig. 2.b. The device operates on the effect of electron tunneling through a multilayer metal-semiconductor superlattice with thicknesses of layers of different materials of several tens of angstroms. Such a device has a negative section on the current-voltage characteristic and can be used to amplify and generate electrical oscillations with a frequency of up to 510 GHz.

The layer of metal and dielectric must be multi-crystalline; epitaxial films of CaF_2 and $CoSi_2$ are very promising materials for the manufacture of this device. Thus, the possibility of forming a superlattice on a silicon substrate seems to be very attractive.

6. Infrared range detectors based on $Si/CoSi_2/$ $Si \ldots CoSi_2/Si$ superlattice. The solution of the quantum-mechanical equation of an electron in a potential well,

indicates that at the corresponding values of the width and depth of the potential well formed in an epitaxial superlattice with alternating layers of metal and semiconductor, the energy spectrum of electrons in metal layers represents a set of discrete levels (and at very small thickness of the metal film there is only one level). The distance between levels can be managed by changing the thickness of the metal layer. In this case, it becomes possible to form a system of levels with energy gap corresponding to the energy of infrared (IR) radiation quanta. The system will change its conductivity when exposed to infrared radiation of the corresponding wavelength, which makes it possible to use the Si/$CoSi_2$/Si… $CoSi_2$/Si superlattice as an infrared detector. The advantage of such a system is its compatibility with silicon technology and the ability to control the spectral sensitivity of IR detectors by changing the parameters of the superlattice, which makes it possible to implement a version of a multicolor IR receiver. Calculations show that it is possible to use such devices to register radiation in the range of 3-5 μ and 8-12 μ.

7. Vacuum ultraviolet-range (VUV) photon detection and ionizing radiation detection. The $CoSi_2$ epitaxial structure can be used to fabricate Schottky barrier photodiodes. Due to specific growth conditions and the growth of a CaF_2 film on top of $CoSi_2$, the detection efficiency in the UV and VUV ranges increases due to the absence of “dead” absorbing layers at the $CoSi_2$/Si interface and on the $CoSi_2$ surface. The described design of the photodetector with an increase in the thickness of the CaF_2 layer makes it possible to implement a version of a monolithic detector of ionizing radiation of the "scintillator-photodiode" type, where the scintillator is CaF_2. The detection layer can also be created on a CaF_2 substrate, on which CoSi and Si layers are sequentially grown (Fig. 3) [11].

8. Devices based on CaF_2:SL/Si superlattice. It was recently found, that, when epitaxial CaF2 films are exposed to electron irradiation, in the bulk of fluorite, clusters of metallic calcium, arranged in an ordered manner, are formed. Due to the fact that calcium and fluorite have close crystal lattice parameters, the structure has a high crystal perfection and is designated as the CaF_2 SL superlattice. The CaF_2: SL superlattice allows epitaxial growth of semiconductors, metal silicides, and the same CaF_2

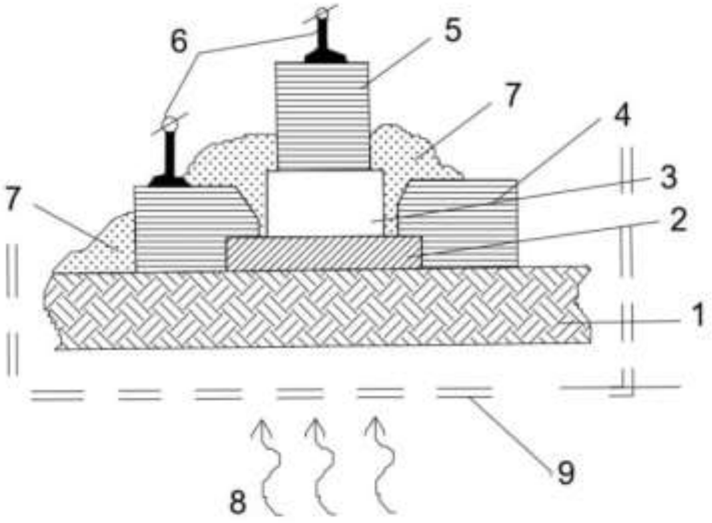


Fig.3. Detector of ionizing radiation

(1- CaF_2, 2- $CoSi_2$, 4-5-Al-contacts, 6-device outputs, 7-SiO_2, 8-ionizing radiation, 9-casing)

The CaF_2:SL structure is characterized by high dielectric constant, which makes it possible to create on its basis devices wherein large charge accumulates in a small space, such as RAM and EPROM with a high density of memory elements.

The CaF_2:SL superlattice selectively formed in CaF_2 layer can find application in the creation of -3-dimensional conductive paths in insulating layers.

It is possible to create devices using the CaF_2:SL threshold conductivity phenomena. Since regularly spaced metallic Co particles are separated from each other by a dielectric material, then at sufficiently low applied voltages, the structure is nonconductive; if the voltage exceeds a certain threshold value, conduction is "switched on" due to the tunneling effect.

In conclusion, it is necessary to mention other promising applications of thin films of calcium fluoride and cobalt silicide, which are not associated with the manufacturing of active device structures of solid-state electronics.

Thus, electron-stimulated effects in CaF_2 make this material attractive for use as an electronic resist in submicron lithography [12]. In this case, a minimum line width of about 100 Å is achieved.

Another useful effect is the change in the optical properties (reflection coefficient, refractive index) of CaF_2 when exposed to electron irradiation, which can find applications in the creation of optical storage devices (memory) with a large memory capacity.

Cobalt silicide films on silicon could also be regarded as a possible candidate for optical storage devices. A thin layer of cobalt deposited on a silicon substrate exposed to laser beam reacts with silicon to form cobalt silicide, which has a different reflectance than cobalt and silicon, which creates an optical contrast under local irradiation.

Finally, effective temperature sensors can be designed on the basis of $CoSi_2$ thin films. In research [13-14] it was shown that cobalt silicide has a linear temperature coefficient of resistance (TCR) in the temperature range 0-400 ^{0}C. This physical property of cobalt silicide in combination with its high chemical and thermal stability, as well as with the possibility of combining it directly with the signal processing circuitry, makes it possible to use the $CoSi_2/Si$ structure for the manufacture of integrated temperature sensors.

Conclusion

In this paper the authors discuss a variety of solid-state electronic devices designed on the basis of different combinations of epitaxial layered dielectric and metal films in silicon technology that allows to create novel devices, including the devices operating on principles of quantum effects.

The paper reports Molecular Beam Epitaxy (MBE) technology for creating a new type of device. Intensive experimental research in the field of epitaxial growth of metals and dielectrics on surface of silicon and the study of their physical properties would most likely in the near future serve as a platform for the increased application of silicon devices that might displace other materials traditionally used in high frequency electronics (A_3 B_5, A_2 B_6), IR and UV - photo electronics.

Jointly with proven methods of epitaxy of various semiconductor materials on a silicon substrate with a buffer layer, the above techniques make silicon technology a universal technology for solid-state electronics and microelectronics.

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