Nanowired structure, optical properties and conduction band offset of RF magnetron-deposited n-Si\(\text{In}_2\text{O}_3\):Er films.

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Abstract

RF magnetron-deposited Si\(\text{In}_2\text{O}_3\):Er films have the structure of the single-crystalline bixbyte bcc \(\text{In}_2\text{O}_3\) nanowires bunched into the columns extended across the films. The obtained films have a typical \(\text{In}_2\text{O}_3\) optical band gap of 3.55 eV and demonstrate the 1.54 μm Er\(^{3+}\) room temperature photoluminescence. The current across the film flows inside the columns through the nanowires. The current through the MOS-structure with the intermediate low barrier \(\text{In}_2\text{O}_3\):Er dielectric was investigated by the thermionic emission approach, with respect to the partial voltage drop in silicon. Schottky plots \(\ln(I/T^2)\) versus \(1/kT\) of forward currents at small biases and backward currents in saturation give the electron forward n-Si\(\text{In}_2\text{O}_3\):Er barrier equal to 0.14 eV and the backward \(\text{In}_2\text{O}_3\):Er barrier equal to 0.21 eV.

1. Introduction

The integration of optical interconnections on a board of chips instead of a metal wiring is the next perspective step in the development of computing systems [1, 2]. The mainstream direction here is to integrate A\(_3\)B\(_5\) light sources on a silicon substrate either by Molecular-Beam Epitaxy (MBE) [1, 3, 4], or by the transfer and bonding technique [1, 2]. It is a technologically complicated, but reliable and perspective way to solve the problem of degradation and aging of the used materials [3–5].

The wide-considered alternative was to dope Si with light-emitting impurities like Er and other rare-earth atoms [6–8]. It has the advantages of simplicity and compatibility with the silicon technology. And the Er\(^{3+}\) inneratomic optical transition \(^{5}I_{13/2}\) → \(^{4}I_{15/2}\) has wavelength 1.54 μm, well-fitting for minimal losses in optical fibers. But, despite significant efforts, the quantum efficiency of Si:Er Light-Emitting Diodes (LED) still remains unacceptably low for applications [8]. The first main unresolved problem here is the technological achievement of high doping of silicon with Er\(^{3+}\) ions in the optically active state [6, 9, 10]. And the second one is the photoluminescence (PL) temperature quenching as a result of the excitation back-transfer from Er\(^{3+}\) to a silicon matrix [6, 11].

On the contrary, the Er\(^{3+}\) PL in a variety of dielectrics and, especially, in oxides is well known [6, 12]. For example, Er-doped optical fiber lasers are widespread and well established [12]. However, they have optical pumping, and the miniaturization for integration purposes would require the Er\(^{3+}\) electrical pumping. This encouraged researchers to investigate the electroluminescence (EL) of Er\(^{3+}\) in SiO\(_2\) [13, 14] and other dielectrics like Si\(_3\)N\(_4\) [15], TiO\(_2\) [16], etc. It was shown that the main Er\(^{3+}\) EL excitation mechanism here is realized by a hot electron impact. It has the excitation cross-section \(6 \times 10^{-15} \text{ cm}^{-2}\) [13]. But a high energy barrier (≈3.2 eV for...
For electrical measurements the n-Si/SiO2 [17]) results in low electron injection currents in the dielectrics and high working electric fields [13–15].

In order to facilitate the electron injection into the dielectric, the Er-doped In2O3 films deposited on Si are considered in this paper. In2O3:Er was chosen because of its presumably small conduction band offsets with Si. In2O3 is considered as a semiconductor with an optical band gap 3.7–3.8 eV [18–22] and indirect band gap 2.69–2.93 eV [18, 19]. Nonetheless, undoped In2O3 can have the natural electron conductivity [23] provided by oxygen deficiency defects, which also give their energy levels in the band gap and are revealed by the visible range PL [24–26]. The Er PL in In2O3 was observed in the literature as well [27, 28]. There is a hope to get the Er EL in the n-Si/In2O3:Er structure, but the knowledge of appropriate barriers for the electron injection is required.

The literature data of Si/In2O3 band offsets are quite rare and scattered. The theoretical calculations gave the negative barrier for electrons going from Si into In2O3 [29]. By the measurements of open-circuit voltage and short-circuit current of Si/In2O3 hetero-junction solar cells, the In2O3 electron affinity was found to be 4.45 eV [30]. Compared with the Si electron affinity of 4.05 eV [17], it gives a negative barrier as well. The authors [29] refer to the unpublished experimental data of Si/In2O3 electron barrier +0.61 eV. The conduction band offset value of the p-Si/In2O3:Mo structure equal to +0.86 eV was obtained by measuring the C–V characteristic in [31]. The In2O3:Sn (ITO) films are well-known transparent conductors and are widely used as transparent contacts to Si [32, 33], and have low barrier values as well.

Despite the above scattered data, there is a common conclusion of a small barrier providing the high electron injection currents from Si into In2O3. The purpose of this paper is to find out the n-Si/In2O3:Er and In/In2O3:Er electron barriers by means of electrical current versus temperature measurements. The RF magnetron-deposited film structure and its impact on the current will also be analyzed.

### 2. Materials and methods

For electrical measurements the n-Si/In2O3:Er/In structures were created on the 6 × 1014 cm−3 phosphorus-doped Cz-Si (100) wafers with resistivity 7.5 Ohm·cm. The wafers were back-implanted with As+ 100 keV, 1 × 1015 cm−2 and annealed at 1000 °C during 1 h in the N2 ambient in order to get the back-contact doping. The wafer surface was cleaned by the RCA process [34]. 220 nm thick In2O3:Er films were deposited on the top surface by means of the RF magnetron sputtering on the BOC Edwards AUTO 500 system. The basic sputtering parameters were as follows: the substrate temperature was 100 °C, the Ar and O2 gas flow rates were 8 and 2 sccm, respectively. The chamber was pumped down to 2 × 10−6 mbar, the working pressure was 6×10−3 mbar, the RF power was 120 W and the deposition time was 50 min. The top electrical contacts sized 0.7 × 0.7 mm2 and the back-contact were performed by the thermal In deposition in a vacuum chamber. The samples for microscopy investigations have slight differences and are described in the relevant parts.

The room temperature (RT) current versus voltage (IV) curves were measured with a Keithley 4200-SCS device. The temperature dependences were measured with the Keithley 2400 device equipped with the temperature control module Linkam LTS420E PB4.

The X-ray photoelectron spectra (XPS) were obtained on a SPECS photoelectron spectrometer with a PHIIBOS-150-MCD-9 analyzer and FOCUS-500 monochromator (AlKα radiation, hν = 1486.74 eV, 200W). The XPS analysis gives the erium content in the deposited films of about 1 at.%. The In3d5/2 peak position at 444.3 eV and the Auger parameter value (BE(In3d5/2) + KE(In MNN) = 850.9 eV correspond to the In3+ state in In2O3 [35].

The samples surface morphology and the structure of deposited films were studied using a Pioneer scanning electron microscope (SEM) manufactured by Raith. The SEM images were made at different electron beam incident angles, including obtaining the images of sample surface plane views and cross-sections, at the incident electron beam energy of 10 keV.

The structural studies of the sample in Si-related (110) cross-sections were carried out by the High Resolution Transmission Electron Microscopy (HREM) with the use of a JEM 2000FS microscope.

The surface morphology and current map through the deposited In2O3:Er films were investigated by the Atomic Force Microscope (AFM) technique by means of Solver P47 PRO (NT-MDT) scanning probe microscope in different operating modes. The surface morphology was analyzed in the contact mode using HA. C/Pt (NT-MDT) cantilevers with a conducting Pt layer. The HA. C/Pt cantilevers force constant working ranges were from 0.2 to 0.8 N m−1, respectively. The equipped scanning spreading resistance microscope mode is commonly used to measure the surface conductivity at local points. It was adapted to obtain the current maps through the deposited In2O3:Er films by contacting the reference electrode to the back In contact. The same samples with the back In contact, as for electrical measurements, were used, except for the top In contact which is absent here. The Pt-covered AFM cantilever, in contact with the In2O3:Er film surface, serves as top electrode here.
The thickness of deposited films and their optical characteristics were obtained with the ISP SB RAS Spectroscopic Ellipsometer ‘Ellips-1991’. The stationary PL was excited by the Nd:YAG laser with the second harmonic generation at 527 nm and the power of 150 mW (200 W cm$^{-2}$). The PL spectra were analyzed by a double grating monochromator ‘CDL-1’ and registered by a nitrogen cooled Ge photodetector. The measurements were performed at RT.

3. Experimental results

The spectral dependences of refractive index $n$ and extinction coefficient $k$ were calculated from the measured ellipsometry characteristics $\Psi$ and $\Delta$ by the linear approximation method [36]. In figure 1 are the calculated $n(\lambda)$ and $k(\lambda)$, where $\lambda$ is the wavelength. The obtained value, e.g., $n = 1.97$ at $\lambda = 550$ nm, is quite close to the literature data: 2.1 for crystalline In$_2$O$_3$ [37], 2.1, 2.17 for Pulse Laser Deposited In$_2$O$_3$ films [38, 39] and 2.1 for ITO [40]. It might strongly depend on the film deposition method and thermal treatment ambient [37–40].

The absorption coefficient $\alpha(\lambda)$ was obtained as $\alpha = 4\pi k(\lambda)/\lambda$. In the insert of figure 1 is the obtained plot for the direct band-to-band absorption analysis of $(\alpha h\nu)^2$ versus $h\nu$ [20, 41], where $h$ is the Plank constant and $\nu$ is the frequency. It gives the optical band gap $E_{\text{opt}} = 3.55$ eV. It is quite close to the values $E_{\text{opt}}$ obtained in the literature: 3.75 eV for crystalline In$_2$O$_3$ [18], 3.55 for plasma-assisted MBE [19], 3.67 for e-beam evaporated [20], 3.73 [21] and 3.67 eV [22] for RF reactive magnetron-sputtered as-deposited In$_2$O$_3$ films. The fundamental band gap of In$_2$O$_3$ has smaller $E_g$ values: 2.69 [18], 2.93 eV [19] and out of the scope here. The conclusion here is that the 1% Er content of In$_2$O$_3$ film does not change its optical band gap noticeably.

The SEM analysis of 570 nm thick In$_2$O$_3$:Er films deposited on the boron-doped Cz-Si (111) wafer with the resistivity of 1.0 Ohm$^*$ cm is presented in figure 2. The complex structure of the deposited In$_2$O$_3$:Er films is revealed here. The films have a nanocrystalline structure and consist of column-like nano-crystals tightly close to each other, extending from the Si substrate to the film surface over all the film thickness. The columns have an irregular shape of a base with a lateral size up to 100 nm. There is a clearance from subnanometers up to 10 nm between adjacent columns. Each column has quite a complex structure as well. It consists of a bunch of thin (up to 10 nm in diameter) crystalline nanowires. They are twisted together in a complex manner with a small clearance (up to 1 nm) between them. The In$_2$O$_3$:Er films deposited on Si(100) (not shown) exhibit the same nanowired-columnar structure as the demonstrated In$_2$O$_3$:Er/Si(111) ones. No wonder why different Si substrates (100) and (111) gave the same film structure. There is a 2 nm thick intermediate SiO$_2$ layer formed between the Si substrate and deposited In$_2$O$_3$:Er film, as it is shown in the HREM image of figure 3 below. This SiO$_2$ layer is amorphous. That is why the Si substrate orientation is irrelevant.

The Si-related (110) cross-section HREM image of 50 nm thick In$_2$O$_3$:Er film deposited on the phosphorous-doped Cz-Si (100) wafer with resistivity 7.5 Ohm$^*$ cm is shown in figure 3. The HREM images were taken...
calibrated with Si <111> interplane distance 3.136 Å (PDF No. 01-075-0589). The HREM analysis confirms the SEM conclusion of the film crystalline nanowired structure. Each nanowire in figure 3 is marked with top and bottom arrows and numbered. The strongest observed planes for each nanowire are indicated in figure 3 with double or single dashes and plane indexes. All nanowires have the same single-crystalline bcc In2O3 structure (PDF No. 01-071-2194). But the crystal orientation of adjacent nanowires is different.

The Er3+ PL measured at RT is shown at figure 4. The spectrum is well agreed to the similar RF magnetron-deposited films in [27] and Er3+ doped In2O3 nanoparticles in [28]. The main peak is at 1.537 μm. The set of ‘red’ side peaks at 1.558, 1.580, 1.600, 1.625 and 1.660 μm is attributed to the Stark splitting of the degenerate ground state 4I15/2. The peaks at 1.625 and 1.660 μm were not observed in [27, 28]. And the set of ‘blue’ side peaks at 1.520, 1.497 and 1.467 μm is attributed to the Stark splitting of the degenerate first excited state 4I13/2. These ‘blue’ side peaks are absent at low temperatures (77K not shown, see also 10K in [28]). The appearance of ‘blue’ side peaks at RT as a result of high power excitation is provided by the temperature Boltzmann population of the upper 4I13/2 Stark levels. The Stark splitting in the Er3+ surrounding crystal field is the result of the state 4I1 Kramers degeneracy (1 + 1/2) reduction depending on the Er3+ atom site symmetry. The authors of [28] performed a detailed analysis of Er3+ Stark splitted states in In2O3 nanoparticles. They came to the conclusion about the C2 symmetry of the Er3+ site different from the regular sites of Er2O3 bcc lattice. Despite the RT PL spectrum similarity with [27, 28], the Er3+ site in the obtained nanowired In2O3 structure is subject of a further research: either in a regular or a defect site of the In2O3 lattice, or at the grain boundaries.

The approximate scheme of the band diagram of n-Si/In2O3:Er In structure at applied positive and negative voltages is presented in figure 5, where Ef is the conduction band, Ev is the valence band, E0 is the Fermi level, φf is the forward barrier at the n-Si/In2O3:Er interface, φB is the backward barrier at the In/In2O3:Er interface, V is
the applied voltage and $V_{ns}$ is the part of the total applied potential $V$, which drops in the silicon Space Charge Region (SCR). The assumption of neither the interface charge nor interface surface states is made here.

The current versus voltage ($IV$) curves through the n-Si/In$_2$O$_3$:Er/In-contact films measured at different temperatures (300, 350 and 360 K) in forward ($0 + 2V$) and backward ($0-10V$) directions are presented in figure 6. At the small positive (forward) voltage applied to the top In electrode, the current is determined by the electron injection from the n-Si substrate into the In$_2$O$_3$:Er film over the forward barrier (figure 5(a)). It has the exponential growth with the applied voltage (figure 6: $0 < V < +0.5V$, see equation (1) in Discussion). At the higher applied voltage, the forward barrier is overcome, and the forward current becomes determined by the In$_2$O$_3$:Er film resistance. It is also shown by the temperature dependence of forward currents. If the forward barrier is not overcome, then the higher the temperature is, the higher the forward current is (figure 6: $0 < V < +0.5V$). It is determined by the electron Boltzmann distribution with a high energy tail to overcome the barrier at higher temperatures in accordance with the thermionic emission approach [17]. At a higher applied voltage,
the forward barrier is overcome, and the forward current is determined by the Si-SCR and In$_2$O$_3$:Er film resistance. The higher the temperature is, the lower the forward current here is (figure 6: $V > 1V$). This could be explained by the mobility reducing as a result of the electron-phonon scattering at higher temperatures [42]. The electron scattering at the nanowire boundaries (figures 2, 3) should be considered as well.

When the negative voltage is applied to the top In electrode, the current flows in the backward direction: electrons are injected from the top In contact into the In$_2$O$_3$:Er film over the backward barrier (figure 5(b)). The backward currents at room and higher temperatures are of saturated character (figure 6 $V < 0$), in accordance with the thermionic emission approach (equation (1) in Discussion). At the low temperature (100K not shown), the backward current is decreased down to the order of $10^{-8} - 10^{-6}$ A cm$^{-2}$ and it has no saturation. It has no clear explanation yet. It could be probably described by the Fowler-Nordheim tunneling current model [17, 43]. The current versus temperature (IT) dependence in Schottky coordinates ($ln(1/T)$ versus $1/kT$) [17] for different applied voltages is presented in figure 7. At the chosen backward applied voltage $-2V$, the IV curve has reached its saturation (figure 6). And at the chosen forward voltages $+0.2$ and $+0.4V$, the forward barrier has not yet been overcome and could be tested by a temperature variation. The backward IT curve is linear in Schottky coordinates from the high temperature down to 170 K (figure 7, red squares curve). The barrier extracted from the curve tilt is equal to 0.21 $±$ 0.01 eV. This supposes the electron injection from the top In contact into the In$_2$O$_3$:Er film by the thermionic emission mechanism over the backward barrier of 0.21 eV (figure 5(b)). At temperatures lower than 170K, the backward IT curve is independent of the temperature (figure 7, red squares curve). It is suggested that the tunneling current mechanism occurs here.

The Schottky plotted forward IT curves at $+0.2$ and $+0.4V$ bias voltages are linear, except for high temperatures, where forward barriers are overcome (figure 7, circular and triangular curves). The extracted tilts are 0.082 and 0.014 $±$ 0.01 eV, respectively. This is equal to the forward barrier reduced by the voltage drop in silicon $\phi_F - V_{ST}$ (figure 5(a)), as it is shown in Discussion.

The obtained columnar structure of the deposited In$_2$O$_3$:Er films could raise some doubts about the current flow mechanism and the nature of the obtained barriers. There arises a question: is the current flow inside the In$_2$O$_3$:Er column or at the column grain boundaries? In order to clarify this question, the map of the current through the deposited film was obtained by the modified AFM technique, as described in the Methods section. First, the surface relief was obtained (figure 8(a)). Then the current through the AFM tip was measured in the scanning mode of following the surface at the same area (figure 8(b)). The direct bias $+1V$ during the current map scanning was applied to the AFM cantilever.

The AFM analysis confirms the columnar structure of the In$_2$O$_3$:Er film in accordance with the SEM analysis above. It gives about a 1 nm surface roughness value in accordance with the SEM and TEM data above. It is shown on the current map in figure 8(b) that the current flows inside the columns. A closer look reveals that the current map of each column consists of small dots indicating the current flows through individual nanowires.

![Figure 6. IV curves of the n-Si/In$_2$O$_3$:Er structure measured at different temperatures. The insert is the forward current $J_f$ versus $V_{Si}/kT$, thermionic emission analysis described in the Discussion section.](image-url)
There is no evidence that the column boundaries have a preferable current flow, except for some occasional places, as indicated with the arrow in figure 8(b). This is the measurement artifact observed between two adjacent columns of equal height because the AFM cantilever has a curvature radius of about 35 nm and collects the parallel currents from both columns here.

Thus, the AFM current map data reveal that the current flows inside the columns. Then the barrier heights found for the electron injection into the In₂O₃:Er film from the Si substrate are still valid.

4. Discussion

The obtained RF magnetron-deposited Si/In₂O₃:Er films have the nanocrystalline columnar structure. Each column consists of a bunch of single-crystalline bixbyte bcc In₂O₃ nanowires of individual orientation. The synthesis of individual In₂O₃ nanowires by different methods is widely reported in the literature [23, 44, 45]. The
In$_2$O$_3$ columns deposited on the glass substrate by the RF magnetron-deposition were presented as well [21]. But the fine structure of In$_2$O$_3$ columns consisting of the bunch of nanowires was resolved here.

It was reported in the literature that the nanocrystalline In$_2$O$_3$ films have the unusually small optical band gap $E_{	ext{opt}} = 2.8$ eV [46], close to the In$_2$O$_3$ indirect fundamental band gap 2.69—2.93 eV [18, 19]. The authors believe that the nanocrystalline structure allows for the otherwise forbidden optical transitions [46]. We found that, despite the nanowired-columnar structure and 1% Er doping, the obtained In$_2$O$_3$:Er films keep the optical band gap $E_{	ext{opt}} = 3.55$ eV within the In$_2$O$_3$ literature data range 3.55—3.74 eV for the films deposited with different methods [18–21]. Therefore, it is supposed that the In$_2$O$_3$ bands are still intact.

The complex nanowired structure raises some doubts about the In$_2$O$_3$:Er film luminescence potential because of structure defects. However, there were no extended defects found in nanowires (figure 3). The point defects are not expected as well, since the close grain boundaries serve as strong sinks for point defects. Thus, the main structural defect in the nanowired In$_2$O$_3$ film would be the nanowire grain boundaries (figures 2, 3). The grain boundary defect is known to be the annihilation center for electron–hole pairs. The used PL pumping at 527 nm provided direct Er$^{3+}$ intracenter photon excitation $^4_{15/2} \rightarrow ^2_{11/2}$ (519.2 nm [28]). Then the In$_2$O$_3$ lattice defects and electron-hole annihilation centers are irrelevant at the 527 nm excitation. However, the Er$^{3+}$ 1.54 mm RT PL was observed at the pumping wavelength 325 nm as well (not shown). At this wavelength, the In$_2$O$_3$ band-to-band absorption through found optical band gap 3.55eV and electron-hole pairs generation occur. Then the electron-hole recombinatiion following the energy transfer into the Er$^{3+}$ excited state $^6_{7/2}$ ($\sim 8000$ cm$^{-1}$ [28]) is possible. The subsequent nonradiative multifoton downshifting gives the observed 1.54 $\mu$m $^1_{13/2} \rightarrow ^1_{15/2}$ PL. If this mechanism is valid, then the potential In$_2$O$_3$ lattice defects annihilation centers can prevent the energy transfer. But the 325 nm pumped Er$^{3+}$ RT PL demonstrates that these defects influence is small enough. The excitation details would be the subject of further research.

So, despite the complex nanowired structure, the RF magnetron-deposited In$_2$O$_3$ films are proved to be suitable host for Er$^{3+}$ RT PL (figure 4), [27, 28]. Then it could be perspective for the EL in Si-based structures providing the low barriers for carriers injection.

The obtained In$_2$O$_3$:Er films have a lateral conductivity below the apparatus sensitivity. It is the intercolumns clearance (figure 2(a)) that prevents the lateral currents. Thus the lateral conductivity and Hall measurements were unavailable for these films.

The current across the In$_2$O$_3$:Er films flows inside the columns through each nanowire, rather then through column grain boundaries (figure 8(b)). Then, the model of adjacent continuous media of In$_2$O$_3$:Er and Si could still be considered and their intermedium boundary could be characterized with a conduction band offset (figure 5). Thus, the overbarrier current will be analyzed with the thermionic emission approach.

The thermionic emission over Schottky barrier is described with equations (1)-(3) bellow [17]:

$$J = J_0 \exp \left( \frac{V}{n k T} \right) \tag{1}$$

and for $V > 3kT$:

$$J = J_0 \exp \left( \frac{V}{n k T} \right) \tag{1a}$$

where $n$ is the ideality factor and $J_0$ is the saturation backward current density given as:

$$J_0 = A R T^2 \exp \left( -\varphi_B / k T \right), \tag{2}$$

from which the barrier height $\varphi_B$ could be calculated as:

$$\varphi_B = k T \ln \left( A R T^2 / J_0 \right), \tag{3}$$

where $AR$ is the Richardson coefficient. $AR$ was taken equal to 120 A cm$^{-2}$/K$^2$ for electrons in silicon [17].

The attempt to approximate the forward currents with equation (1a) gives an unreasonably high ideality factor $n$ from $n = 3.5$ at $T = 300$ K to $n = 5$ at $T = 360$K (not shown). The authors of [47] get the same result with the ideality factor $n = 6$ for sol-gel thin films on silicon.

Since the Metal–Oxide–Semiconductor (MOS) In$\chi$/In$_2$O$_3$:Er–n–Si structure has the intermediate low barrier In$_2$O$_3$:Er dielectric (figure 5), then the total applied voltage ($V$) has two parts: one is applied to Si ($V_{\text{Si}}$) and the other—to the In$_2$O$_3$ dielectric. In order to correct equation (1a) for the thermionic emission over a low barrier dielectric, it is required to consider only that part of the applied voltage which drops in silicon, since only the voltage, which drops in silicon, reduces the barrier for the electron thermionic emission over $\varphi_{\text{Si}} - V_{\text{Si}}$ (figure 5(a)). Then the equation (1a) is transformed into:

$$J = J_0 \exp \left( V_{\text{Si}} / k T \right). \tag{1b}$$

The calculation of $V_{\text{Si}}$ versus applied $V$ was obtained from the numerical solution of the Poisson equation for the Si/In$_2$O$_3$:Er structure in Boltzmann approximation. It could also be easily found from the calculated curves for the Si/SiO$_2$ structure in [17] with the correction to the In$_2$O$_3$ relative dielectric constant of $\varepsilon_{\text{In2O3}} = 8.9$ [32, 48]. The plots of forward current density $J$ versus $V_{\text{Si}}/k T$ are presented in the insert of figure 6 with symbols. They
were approximated with equation (1b) for the case $V_\text{Si} > 3kT$. The approximations are presented there with lines. The obtained approximation parameters $I_{df}$, $n$ and $\varphi_B$, calculated with equation (3), are presented in Table 1 below. As it could be seen, the correction of $V_\text{Si}$ versus $V$ makes the thermionic emission approach (1b) describe the forward currents with reasonable parameters $I_{df}$ and $n$ quite well.

At $T = 360 \text{K}$, the obtained $I_{df}$ is less than at $T = 350 \text{K}$ (Table 1). However, it should grow as $I_{df} \sim T^2$ at high temperatures, according to equation (2). This indicates that, at these temperatures, the small forward barrier is comparable with $3kT$ and it is easily overcome. Thus, the current is determined with the In$_2$O$_3$ film resistivity. And the electron-phonon scattering process is increased with the temperature rise [42] giving the decrease of current here.

The backward saturation current ($I_{sb}$) found as the backward current at small backward bias $V = -2V$, where the saturation was reached (figure 6), is presented in Table 1 as well. It well agrees to the forward one ($I_{df}$) except for high $T = 360 \text{K}$, because the above-mentioned forward current reaches the overbarrier state.

The forward barrier height, obtained with equation (3), have value $\varphi_B = 0.6–0.7 \text{ eV}$ (Table 1). It looks reasonable and close to some literature data: $0.61$ for Si/In$_2$O$_3$ [29], $0.63$ for Si/In$_2$O$_3$:Er [47] and $0.86$ eV for p-Si/In$_2$O$_3$:Mo by C–V measurements [31]. However, let’s compare it with the forward barrier height found by the temperature variation below.

The Schottky plotted forward IT curves at $+0.2$ and $+0.4$ bias voltages give the tilts of $0.082$ and $0.014 + 0.01$ eV, respectively (figure 7). This is equal to the forward barrier reduced by the voltage drop in silicon $\varphi_f - V_\text{Si}$ (figure 5(a)). The voltage drop in silicon was found as described above: $V_\text{Si} = 61$ and $94 \text{ mV}$ for applied $V = +0.2$ and $0.4 \text{ V}$, accordingly. It gives the following forward barrier values: $\varphi_f = 0.14$ and $0.11 \text{ eV}$, correspondingly. The lower barrier value at $V = 0.4 \text{ V}$ could be related to the approaching of barrier overcoming and initiating of an additional current mechanism, e.g., tunneling. It is consisted with the declination of the forward IT curves from the linear Schottky plot at $T = 300–350 \text{K}$ (figure 7, circular and triangular curves). At these temperatures, $3kT = 75–90 \text{meV}$ is comparable to the found forward barrier height $0.14 \text{ eV}$. Thus, it becomes overcome.

The found backward barrier $\varphi_B = 0.21 \text{ eV}$ remains valid since the backward applied voltage does not affect the backward barrier (figure 5(b)).

The barriers found by the temperature variation ($\varphi_f = 0.14 \text{ eV}$ and $\varphi_B = 0.21 \text{ eV}$) are significantly lower than the ones found by equation (3) out of saturation currents $I_{df}$ and presented in table 1. It means that the Schottky barrier equations (2), (3) and mostly pre-exponential ($\exp(\Delta R^*T^2)$) could be inappropriate for the considered case of the MOS-structure with an intermediate low-barrier dielectric. But the main barrier dependence $J_s \sim \exp(-\varphi_B/kT)$ is still valid. Therefore, the barriers found by the temperature variation are most trustworthy, compared to the ones given in Table 1.

### Table 1. Parameters ($I_{df}, n$) of the experimental forward $I$-$V_\text{Si}$ curve approximation by the thermionic emission approach (1b) with the corrected voltage drop in Si ($V_\text{Si}$). The barrier height $\varphi_B$ was calculated from $I_{df}$ in accordance with equation (3). $I_{sb}$ is an approximation of backward saturated currents at small negative values $V$.

| Parameters | $I_{df}$ A cm$^{-2}$ | $n$ | $\varphi_B(I_{df})$, eV | $I_{sb}$ A cm$^{-2}$ |
|------------|----------------------|----|------------------------|----------------------|
| $T$: K     |                      |    |                        |                      |
| 360        | $3 \times 10^{-3}$   | 1.45 | 0.69                   | $5.9 \times 10^{-3}$ |
| 350        | $5.1 \times 10^{-3}$ | 1.26 | 0.66                   | $4.8 \times 10^{-3}$ |
| 300        | $1.2 \times 10^{-3}$ | 0.9  | 0.59                   | $1.3 \times 10^{-3}$ |

5. Conclusion

It is shown that the RF magnetron-deposited Si/In$_2$O$_3$:Er films consist of the single-crystalline bixbyite bcc In$_2$O$_3$ nanowires bunched into columns extended across the films.

The nanowired-columnar structure and the 1% Er doping of films do not affect the optical band gap of In$_2$O$_3$, $E_{\text{opt}} = 3.55$ eV.

The obtained In$_2$O$_3$ films are the suitable host for the Er$^{3+}$ RT PL.

The AFM current map shows that the current across the film flows inside the columns through the nanowires.

The MOS-structure n-Si/In$_2$O$_3$:Er/In with intermediate low-barrier dielectric In$_2$O$_3$:Er could be described by the thermionic emission approach with the correction of the total applied voltage into the voltage dropped in silicon.
By the temperature variation of backward currents in saturation, plotted in Schottky coordinates, the backward barrier $\varphi_b = 0.21$ eV was found for the electron injection from the metallic In contact into the dielectric $\text{In}_2\text{O}_3$:Er film. By using the Schottky plots of forward currents at small biases (lower than the barrier) and considering the voltage dropped in silicon, the forward barrier $\varphi_F = 0.14$ eV was found for the electron injection from the n-Si substrate into the dielectric $\text{In}_2\text{O}_3$:Er film. The obtained results give an impulse for a further investigation of Si/In$_2$O$_3$:Er films for silicon-compatible light-emitting applications.

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