

Comparison of turn-on characteristics of thyristor structures based on wide bandgap materials

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Abstract. The aim of this paper is to investigate the behaviour of the break-over voltages of thyristor structures, based on wide bandgap materials, under different conditions. Influence of the narrow and wide base width, electron/hole lifetime, shunt and collector resistance, donor/acceptor concentration, temperature, and charge carrier recombination time on the break-over voltage has been investigated and analysed. On the basis of this information it is possible to make suggestions to the designers of the device to avoid expensive practical experiments.

Key words: wide bandgap materials, thyristors, break-over voltage, electron lifetime, shunt resistance, donor concentration, charge carrier.

1. INTRODUCTION

Wide bandgap (WBG) semiconductor devices, which are based on silicon carbide (SiC), gallium nitride (GaN), diamond (C) and semi-wide-gap semiconductor material gallium arsenide (GaAs) as well, demonstrate promising properties under extreme conditions, such as high power, high temperature and high frequency. The ability of WBG semiconductors to function under extreme conditions is expected to allow significant improvements to a large variety of systems and applications, such as electrical motor control, electronic actuators, power supplies, heating and cooling systems, car and jet engine electronics, spacecrafts, chemical reaction monitoring, communication systems, radars, UHF broadcasting etc. One of the most promising fields, where WBG devices might be used, is power electronics converters. There is a number of improvements expected,

including higher switching speed, higher blocking voltages and switching frequencies and lower switching losses.

The aim of this work is to develop a 1D numerical model for the power thyristor structures, to design a simulation algorithm and to run simulations for thyristor structures on the basis of different materials (Si, SiC, GaN, GaAs, C). We also investigate the dependence of forward switching properties on the electro-physical and technological parameters like narrow and wide base widths, electron/hole lifetime, shunt and collector resistances, donor/acceptor concentrations, ambient temperature and capture times of charge carriers recombination.

2. DESCRIPTION OF THE MODEL

The maximum forward switching voltage is the value of applied voltage when thyristor switches from the off to the on state and the voltage is not applied to the control terminal. On the straight branch of the voltage–current characteristic this corresponds to the junction through the point, at which the dynamic resistance is equal to zero and forward voltage attains its maximum value.

The structure and the impurity distribution of a typical thyristor structure are shown in Fig. 1.

The total current I , starting the flow from the anode region p_1 and reaching the cathode region n_2 , is influenced by the integral coefficient of the majority carriers (holes for $pnpn$ structures and electrons for the $npnp$ structures) injection of junction J1, by the integral transfer coefficient of the minority carriers (holes for $pnpn$ structures and electrons for the $npnp$ structures) through wide

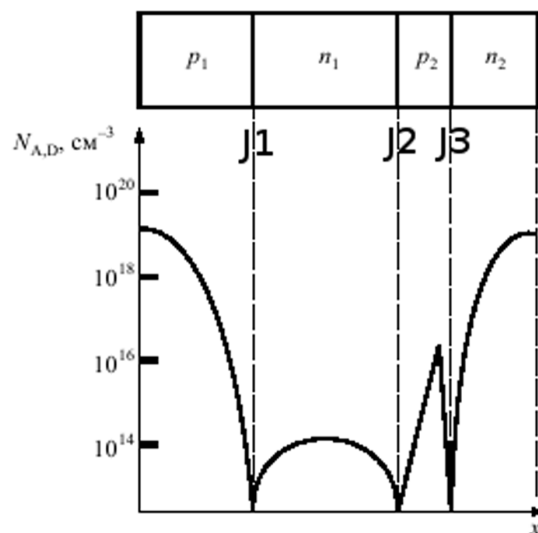


Fig. 1. Thyristor structure.

base, and by the avalanche multiplication of charge carriers, taking place in the collector junction at relatively high forward voltages. Majority carriers (electrons for *pnpn* structure and holes for *npnp* structures) form an additional current and it is possible to characterize the movement of the majority carriers (electrons for *pnpn* structures and holes for *npnp* structures) that are injected by the junction J3 into the narrow base in the same way. In this case, it is necessary to consider that the junction J3 has an artificial ohmic leakage – a shunt with the resistance R_{sh} . Besides the “gathered” currents, the total current of collector junction J2 contains its own return current, which consists of three components. The current I_{g20} , caused by the generation of carriers in the layer of the space charge of junction, is the most important of them. The current of surface leakage is determined by a certain equivalent leakage resistance R_{l2} . Consequently, the total current through the collector junction can be written as

$$I_2 = M_{p2}K_p\Gamma_1I + M_{n2}K_n\Gamma_3I + M_{g2}I_{g20} + \frac{U_2}{R_{l2}}, \quad (1)$$

where M_{p2} , M_{n2} and M_{g2} are the multiplication coefficients for holes, electrons and generated charge carriers, respectively (Miller’s model), K_p and K_n are the transport coefficients for holes and electrons, Γ_1 and Γ_3 are the efficient coefficients of junction J1 and J3, R_{l2} is the leakage resistor, U_2 is the applied voltage at the junction J2, I_{g20} is the generation current at the junction J2 and I is the total current.

If a voltage is applied to the thyristor structure, we set $I_2 = I$ and $U_2 = U - U_1 - U_3 \equiv U$, and thyristor switching characteristic can be expressed in the form

$$I = (M_{p2}X_p\Gamma_1 + M_{n2}X_n\Gamma_3)I + M_{g2}I_{g20} + \frac{U}{R_{l2}}, \quad (2)$$

where $X_p \equiv K_p$, and $X_n \equiv K_n$ are the integral transport coefficients of charge carriers both in wide and narrow base regions of the thyristor structure and generation current writes as

$$I_{g20} = \frac{qn_i l_{2n} S_2}{2\sqrt{\tau_{p0}\tau_{n0}} \cosh\left(\frac{\Delta w_t}{kT} + \frac{1}{2} \ln \frac{\tau_{p0}}{\tau_{n0}}\right)}, \quad (3)$$

where q is the electron charge, n_i is the intrinsic concentration, k is the Boltzmann coefficient, T is the absolute temperature, τ_{p0} and τ_{n0} are capture times of the charge carriers, Δw_t is the energy gap, l_{2n} is the thickness of the space-charge region and S_2 is the junction area.

The general forward switching condition for thyristor structures is [1]

$$\frac{dI}{dU} = \infty. \quad (4)$$

This condition can be rewritten as

$$M_{p2} X_p \gamma_1 + M_n X_n \gamma_3 = 1, \quad (5)$$

where $\gamma_n \equiv \Gamma_n$, $\gamma_p \equiv \Gamma_p$ are the integral junction injection efficiencies for electrons and holes, respectively.

For the solver, the open source platform for numerical computation Scilab (version 4.1.1.) [2] was chosen to simulate the thyristor maximum switching voltage. The general block diagram of the algorithm is presented in Fig. 2.

The data for the Miller's avalanche breakdown model, for the recombination/generation model parameters, for the charge carriers lifetime data, for the lattice parameters for isotropic semiconductors and for other global model parameters are taken from literature [3-7].

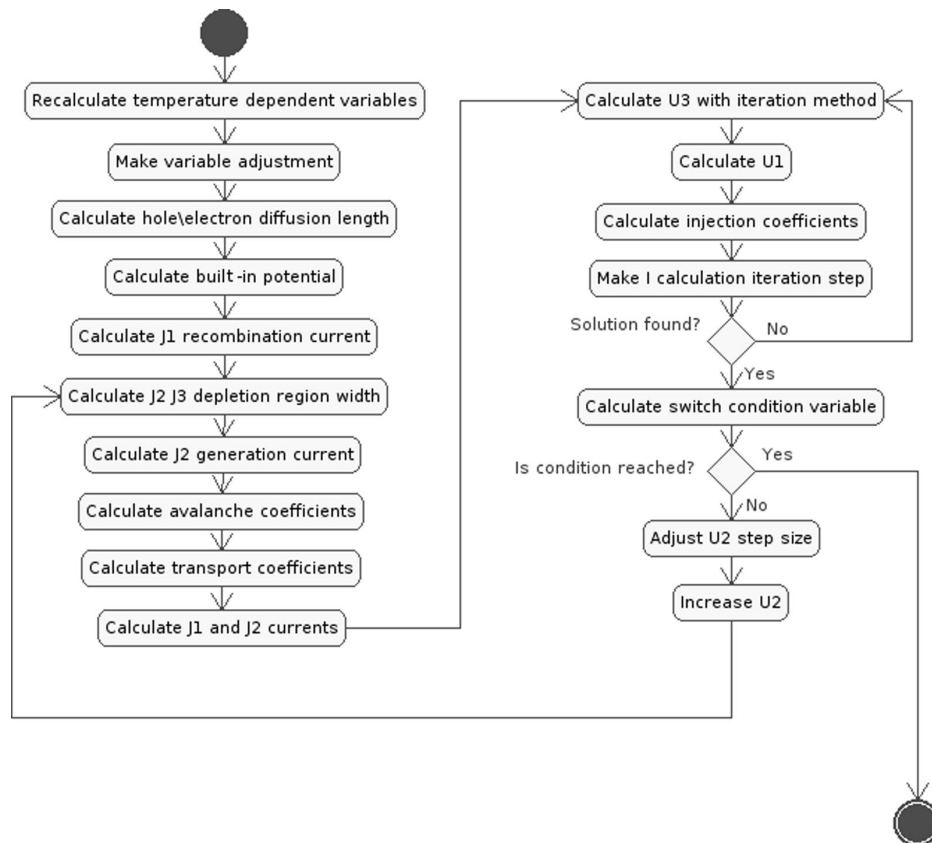


Fig. 2. Block diagram of the simulation algorithm.

3. RESULTS AND DISCUSSION

Four different basic materials for thyristor structures were investigated. Silicon was used as the reference material, GaAs as a semi-wide bandgap material and SiC, GaN and C (diamond) as wide bandgap materials. The most important geometrical and technological parameters and the ambient temperature were used as variables in the developed model.

3.1. Example one: influence of the base width on the break-over voltage

The influence of the narrow base width was investigated, but the simulation results showed clearly that the width of the narrow base has no practical influence on the forward break-over voltage U_{bo} . It can be explained by the fact that the effective width of the thin base region is sufficiently constant due to the relatively high impurity concentration in this region and therefore the acceptable changes in the geometry have little influence on the forward break-over voltage U_{bo} . The simulation results showed clearly that the sensitivity curve is close to a straight line, showing the dependence of the voltage on the depth.

At the same time, the influence of the wide base width is significant and the forward break-over voltage U_{bo} is pretty sensible to the change of the width of the wide base region. Figures 3a to 3e show the dependence of the forward break-over voltage U_{bo} on the width of the wide base w_2 of the thyristor structure. The behaviour of U_{bo} can be understood taking into account that the effective base width of the wide base strongly changes due to applied biases and relatively low impurity concentration in this particular region (the width of the space charge region increases mostly into the wide base). Simulations show also a different behaviour of the function $U_{bo}(w_2)$ for Si and C (diamond) compared to other materials (GaAs, GaN and 6H-SiC) based thyristor structures. As one can see, the slope of the curve is opposite for Si and C compared to GaAs, GaN, and 6H-SiC. The reason for this behaviour is the variation of the forward break-over voltage U_{bo} itself. For Si and C, the growth of the sensitivity is taking place rapidly when the wide base width increases and the growth starts to saturate, which indicates that later on the increase of the width is less critical compared to the increase in the beginning. It is caused by the change of the effective wide base thickness at acceptable specific impurity concentration for the wide base region. For the other materials based thyristor structures the sensitivity increases and at larger widths the increase is more rapid compared to smaller widths. Here very clear explanation is missing and the problem needs further theoretical and experimental investigations. We guess that the combined influence of the recombination capture time of charge carriers with generation and leakage currents causes such a character of the function $U_{bo}(w_2)$.

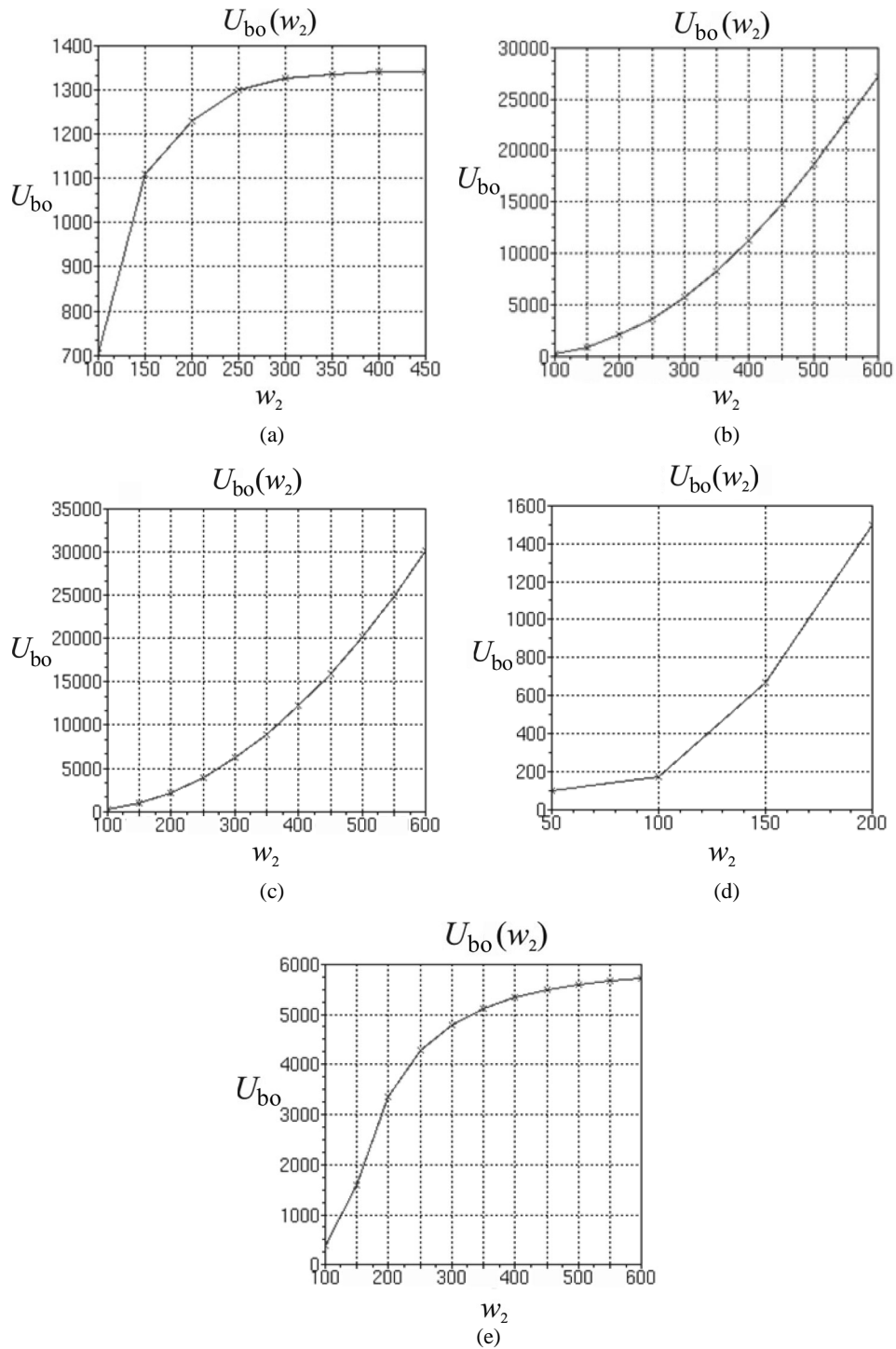


Fig. 3. The forward break-over voltage U_{bo} [in V] dependence on the wide base width w_2 [in μm] for Si (a), SiC (b), GaN (c), GaAs (d), and C (diamond) (e) structures.

3.2. Example two: influence of the shunt resistance and of the spreading resistance of junction J2 on U_{bo}

The surface leakage is expressed by the shunt resistance R_{12} and it has significant influence on Si based solutions, but much weaker influence on structures based on other materials. The explanation follows from the generated current itself, which mostly determines the surface leakage current of junction J3 in thyristor structures and from technological parameters of the material of the base. The measurable values were reliable only in case of Si based thyristor structures.

The spreading resistance of junction J2 is a sum of the junction impedance and total current voltage through the junction and therefore the spreading resistance reaches the values clearly influencing the forward break-over voltage U_{bo} . Figures 4a to 4e show the dependence of the forward break-over voltage U_{bo} on the spreading resistance of junction J2 of the thyristor structure. The dependences are rather linear. The simulations show, however, much larger changes in the values of the spreading resistance of the junction J2 than one can follow in real structures and therefore it can be concluded that this parameter has some influence on forward break-over voltage U_{bo} , but as model parameter has secondary level influence and practically can be neglected in the majority of situations.

3.3. Example three: influence of the ambient temperature on U_{bo}

All thyristor structures are strongly influenced by the ambient temperature. There are no simulation results for C (diamond) due to considerable uncertainty in the definition of the density of states of effective masses. Figures 5a to 5d show the dependence of the forward break-over voltage U_{bo} on the ambient temperature of the thyristor structures. Big difference of sensitivity characteristics for Si and GaAs based thyristor structures and thyristor structures based on wide bandgap materials can be observed. The main reason for that is the strongly different behaviour of the multiplication phenomena (the scattering processes) in Si and in structures based on wide and semi-wide bandgap materials. The scattering processes still show some similarity in Si and GaAs based structures, where U_{bo} decreases with the temperature, but in a different way. SiC and GaN behave in an opposite way, but the sensitivity versus temperature matches well with each other, which indicates to similar behaviour of scattering processes in these materials.

The investigations covered also the influence of electron lifetime in the narrow base and holes lifetime in the wide base on U_{bo} , the influence of donor concentration in the wide base and the acceptor concentration in the thin base on U_{bo} and the influence of charge carriers' recombination centres capture time on U_{bo} .

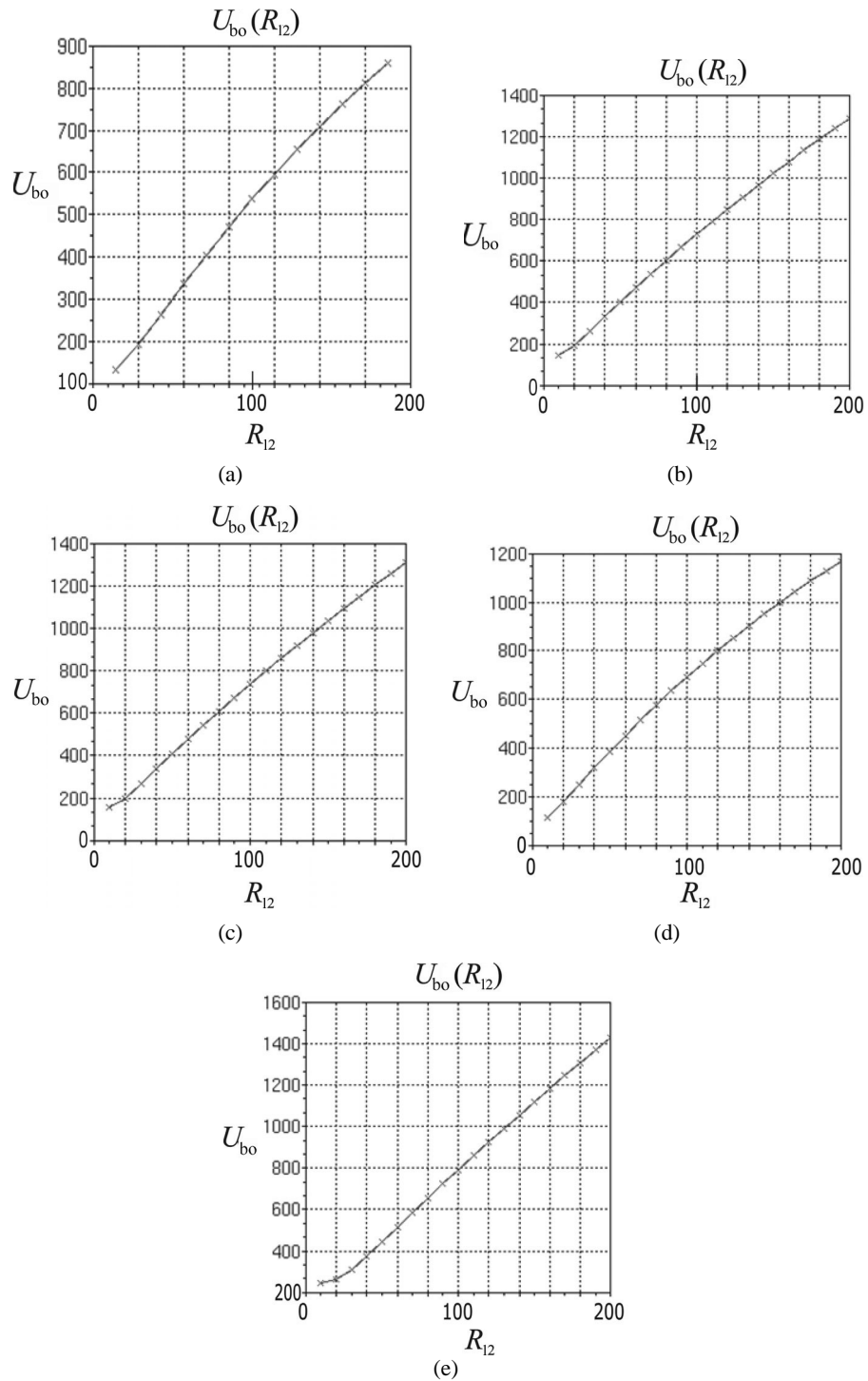


Fig. 4. The dependence of forward break-over voltage U_{bo} [in V] on spreading resistance R_{12} [in Ohms] of junction J2 for Si (a), SiC (b), GaN (c), GaAs (d), and C (diamond) (e) structures.

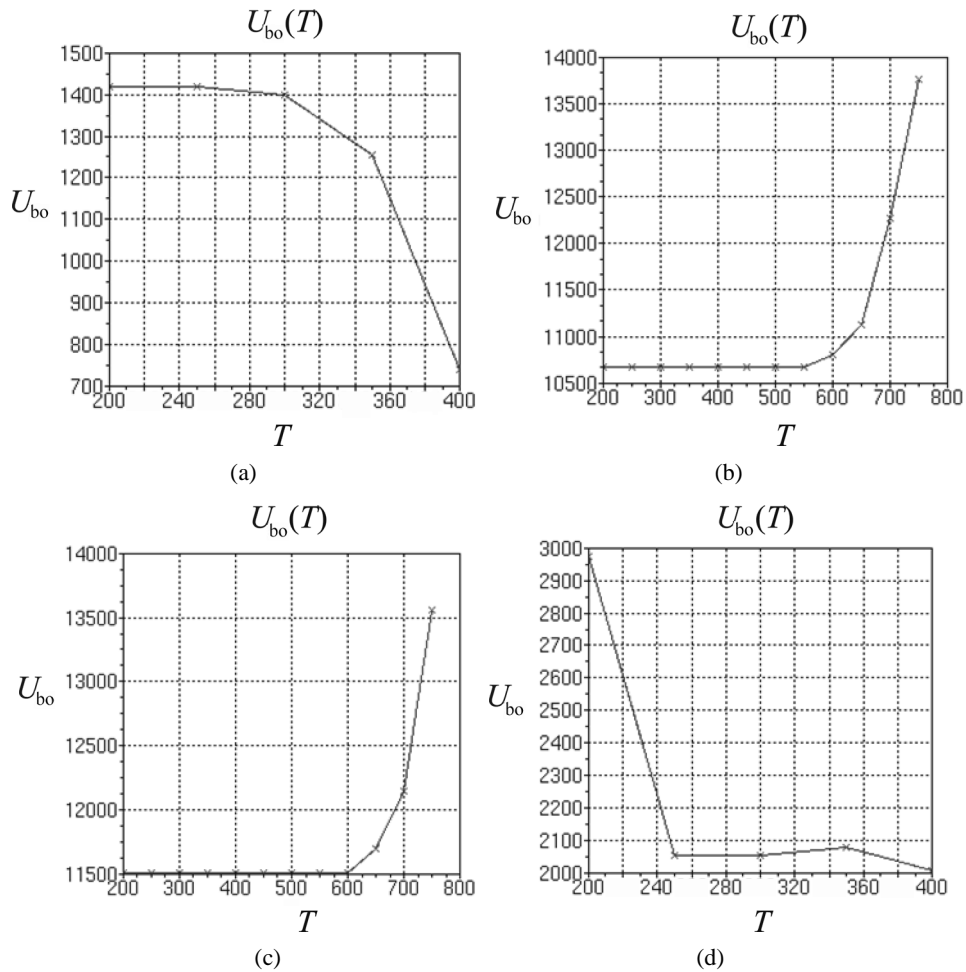


Fig. 5. The dependence of forward break-over voltage U_{bo} [in V] on ambient temperature T [in Kelvin] for Si (a), SiC (b), GaN (c), and GaAs (d) structures.

The simulations show that the minority carrier's lifetime in the wide base has some influence on the forward break-over voltage U_{bo} . The influence of donor or acceptor impurities in the wide or thin base has strong influence on the forward break-over voltage U_{bo} , but here the explanation is very simple. Due to the fact that these concentrations directly have influence on junction breakdown voltages and effective thicknesses of the layers, through these two mechanisms the forward break-over voltage U_{bo} is strongly influenced.

The recombination capture times of charge carriers and its influence on forward break-over voltage U_{bo} leads to the conclusion that the influence exists, but it is not critical and could be neglected.

4. CONCLUSIONS

The simulation results show clearly that the maximum thyristor switching voltage U_{bo} for any semiconductor material is mostly influenced by the wide base width, collector junction spreading resistance and ambient temperature. For diamond, temperature characteristics were not calculated, because of considerable uncertainty in the temperature behaviour of the density of the states of effective masses. However, influence of holes (minority carriers) concentration in the wide base is visible for both wide bandgap and non-wide bandgap materials based thyristor structures; we can avoid them in the first order by the modelling of the thyristor structures. Other parameters, such as electron lifetime in the thin base and capture time of recombination centres do strongly influence maximum thyristor switching voltage and can be neglected in many cases.

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Laia keelutsooniga materjalidel põhinevate türistorstruktuuride ümberlülituskarakteristikute võrdlus

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On kirjeldatud ühedimensioonilist mudelit türistorstruktuuride ümberlülituspinge käitumise uurimiseks. On uuritud laia keelutsooniga materjalidel realiseeritavate türistorstruktuuride ümberlülituspinge sõltuvust struktuuride sisemistest elektrofüüsikalistest (laengukandjate eluiga ja rekombinatsioonikestus) ning tehnoloogilistest (lisandite kontsentratsioon, baasialade paksus, šundi takistus) parameetritest ja välistingimustest (temperatuur) eesmärgiga välja selgitada kriitilised parameetrid, mis mõjutavad türistorstruktuuride ümberlülituspinget.