DRIFT AND HALL MOBILITY OF HOLE CARRIERS IN STRAINED SiGe FILMS GROWN ON (001) Si SUBSTRATES

G. Dimitrov, Mohamed A. Abdulah, N. Goranova

Faculty of Electronic Engineering and Technology, Technical University-Sofia
"Kl. Ohridiski" No.8, 1000 Sofia, Bulgaria

tel. +359888282766 e-mail: mohamed@ecad.tu-sofia.bg

Drift and Hall mobility of hole carriers in strained SiGe films grown on (001) Si substrates: SiGe/Si bipolar heterojunction transistors (HBTs) have become widespread nowadays due to their unquestioned advantages over the Si bipolar junction transistors. When simulating the dc-regime of SiGe NPN HBT, as well as designing the new transistors, the input parameters are the collector current Jc, and the sheet resistance of the base R_{SB}, which depend on the mobility of the base minority n-carriers and majority holes, respectively.

This paper presents an extensive overview on the influence of the dopant concentration, Ge content, and SiGe strain on the drift and Hall carrier mobility. We show the mathematical description of the dependence μ_d^p, $\mu_H^p = f(N_{imp}, X_{Ge})$, which can be used at the simulation of the dc-regime of SiGe HBT, and also we give an equation relating J_c and R_{SB}, which accounts for the effect of active base narrowing at high dopant levels.

Keyword: Drift mobility, hall mobility, hole carriers, SiGe films, bipolar heterojunction transistors.

INTRODUCTION

Drift mobility μ_d and hall mobility μ_H are reflecting the zone structure of the semiconductor in different manners. They are equal for parabolic and spherical zones and if the scattering time is energy independent.

The ratio between hole and drift mobility is defined as hall scattering coefficient r_H:

(1) $$\mathbf{r_H} = \mu_H^p / \mu_d^p$$

Because of the changes in the energy bands in $Si_{1-x}Ge_x$ due to the maximum strain, the effective hole mass m_{eff}^p [1] is decreased compared to that in the bulk Si, which results in a higher drift mobility [2, 3]. The scattering of $Si_{1-x}Ge_x$ alloy on the other hand decreases μ_d^p. Some experimental data [4] confirm the increase of μ_d^p with the increase of X_{Ge} at constant dopant concentration N_{imp} = const.

The narrowing of E_g in the transistor base depends on the Ge content and maximum strain in $Si_{1-x}Ge_x$. As the matching is accompanied by strain in the epitaxial layer, this layer is pseudomorphous. In fact the pseudomorphous $Si_{1-x}Ge_x$, grown above (001) Si could be used as a base area of NPN heterojunction bipolar transistors for UHF applications [5, 6].

MAIN PART

1) Hole drift mobility

The design and simulation of UHF HBT and IC with embedded SiGe HBTs requires investigation of transport properties of carriers, and here the mobility of the major and minor carriers is one of the basic parameters. The available data about strained layers is quite limited by the critical thickness d_{cr} and precise definition of the free carrier concentration. In [2, 7, 8] a transport theory for holes in strained and unstrained $Si_{1-x}Ge_x$ is discussed. A slight increase of μ_d^p in strained $Si_{1-x}Ge_x$ is observed compared to drift mobility of holes in bulk Si, and for $X_{Ge} > 0.40$ (40%) μ_d^p dramatically increases. Some theoretical investigations of drift mobility in strained $Si_{1-x}Ge_x$ layer are performed in [2, 9], using Monte Carlo (MC) simulation. Compared to scattering in Si, the only additional mechanism in $Si_{1-x}Ge_x$ is the scattering from Ge alloy. For the design and simulation of operation of HBT it is important to know the value and behavior (variation) of μ_d as related to Ge content $\mu_d = f(X_{Ge})$. The function $\mu = f(E, N_{imp}, X_{Ge})$ is used as input parameter for the simulated solution of equations "drift - diffusion" for optimization of dopant and Ge profiles.

The determination of mobility through MC simulation requires enormous computing resources to achieve a stable value of μ_d. That's why a simple and time saved method for calculation of μ_d in $Si_{1-x}Ge_x$ is offered in [10].

Hall and drift lateral component of the mobility in strained p-type LPCVD and MBE grown $Si_{1-x}Ge_x$ samples with boron concentration $N_{imp} = 10^{18} \div 10^{20}$ cm^{-3} are measured in [11]. It is determined, that the apparent drift mobility μ_d^{app} increases with x_{Ge}, and the Hall mobility μ_H^p decreases for all doping levels. Mobility depends on the dopant concentration, Ge content, temperature, strain and critical thickness of the grown SiGe layer i.e. $\mu = f(N_{imp}, X_{Ge}, t°, \text{strain}, d_{cr})$.

In the publications dated 1991÷1993 was stated about an increase of μ_d with the increase of X_{Ge} in MBE deposited $Si_{1-x}Ge_x$. McGregor et al [4] determined that the apparent μ_d increases, and μ_H decreases with the increase of X_{Ge} at $N_{imp} = 1,5 \div 2.10^{19}$ cm^{-3}. In [11] the behavior of μ_d and μ_H at $X_{Ge} = 0 \div 0{,}20$ and $N_{imp} = 10^{18} \div 10^{20}$ cm^{-3} - values of X_{Ge} and doping, which are most frequently used for the fabrication of SiGe HBTs [12]. With the increase of X_{Ge} an increasing of μ_d^{app} and decreasing of μ_H is observed. The explanation of this phenomenon is hidden in the Hall scattering factor and in the changes of the valence zone.

The μ_d^{app} of compressed strained $Si_{1-x}Ge_x$ layers is determined in two ways - SIMS or measurement of the specific mobility using van der Pauw method and calculation with the formula:

(2) $$\mu_d = 1/(e.\rho.N_a)$$

The mobility is stated as "apparent" because using SIMS the total boron concentration is measured, which in case of partial ionization of the atoms is different from the free carrier concentration. After Matutinovic et al [13] acceptance of full dopant (boron) activation is a correct one, as for emitter deposition at $t° \geq 800^oC$ for more than 5 min (7, 5 min in this case) in-situ doped $Si_{1-x}Ge_x$ base layer is fully

activated. The effects of E÷B and C÷B depletion layers change the total charge in the base in the weak doped (10^{18} cm^{-3}) base regions with about 10%, and in heavily doped layers - with 1% only. With the increase of x_{Ge} the hole concentration decreases, as the state density in the valence band N_υ decreases [7, 14]. At non-complete ionization, the dopant concentration is greater than the carrier concentration, and the difference of the mobility ($\mu_d^{app} - \mu_d^{real}$) slightly increases with the increase of X_{Ge}.

With the increase of the doping levels from 10^{18} to 10^{20} cm^{-3}, μ_d^{app} decreases due to the increase coulomb scattering - Fig.1

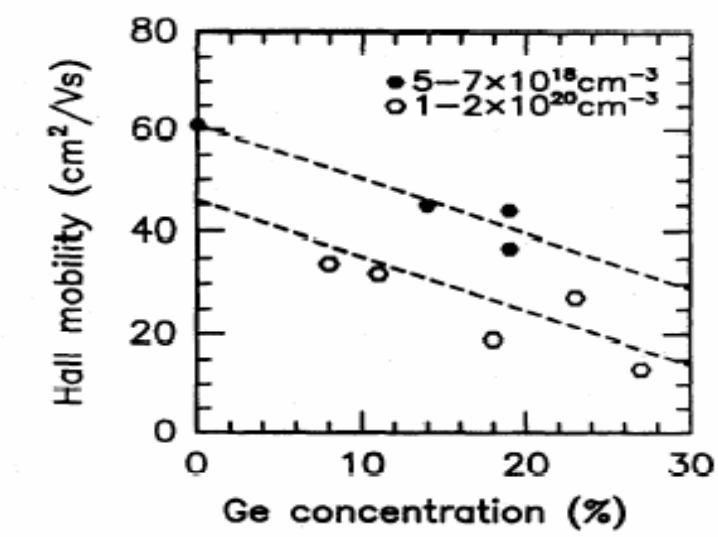

Fig.1 $\mu_H^p = f(X_{Ge})$ at two doping levels of the base region.

With the increasing of X_{Ge}, μ_d^{app} increases. With the increasing of the interaction potential U_o, the drift mobility decreases. After [15], accepted later by [11], the relation $\mu_d^p = f(N_{imp}, X_{Ge})$ could be described by the formula:

(3) $$\mu_d^p = \mu_{min} + \mu_o/[1+ (N_{imp}/2{,}75.10^{17})^{\alpha}]$$

Where: $\mu_{min} = 44 - 20X_{Ge} + 850X_{Ge}^2$; $\mu_o = 400 + 29\,X_{Ge} + 4737X_{Ge}^2$; $\alpha = 0, 9$

The experimental data, obtained by Carns et al [10] are almost ≈50% lower than the calculated by Chun and Wang values for μ_d^p [14.

Hall mobility

In the investigation performed in [10], Hall mobility on strained $Si_{1-x}Ge_x$ decreases with increasing of x_{Ge} for the whole doping range ($10^{18} \div 10^{20}$ cm^{-3}), and the error bar in the measurement of μ_H is significantly smaller (8%) than that for μ_d (±37%, typ ±20%). An equation similar to (3) is used for determination of μ_H:

(4) $$\mu_H^p = \mu_{min} + \mu_o/\,[1+ (N_{imp}/2,\,75.10^{17})^{\alpha}]$$

Where $\mu_{min} = 37 - 61X_{Ge}$; $\mu_o = 440 - 632X_{Ge}$; $\alpha = 0, 9$

Similarly to μ_d, μ_H^p is slightly influenced by the growth method of $Si_{1-x}Ge_x$ (MBE or CVD) for $X_{Ge} \leq 0.20$.

Hall scattering coefficient r_H decreases with the increase of $X_{Ge.}$ Matutinovic - Krstelj et al. [13] obtained similar results in the measurement of μ_d and μ_H in strained

$Si_{1-x}Ge_x$, but the interpretation of the relation $\mu_d^p = f(X_{Ge})$ is different. After [6] the effects of scattering from the alloy and changes in the energy level density should be taken into account for $Si_{1-x}Ge_x$ layers.

The carrier scattering in strained $Si_{1-x}Ge_x$ layers is different than scattering in Si, adding scattering from the alloy and at the same time significant decrease of the scattering in the intravalence and intervalence zone, due to the strain inducted zone split. Finally, with the increase of B concentration, tension of tensile appears which results in a more complicated structure of the valence band and scattering mechanism.

Fig. 2 shows the relation $\mu_H^p = f(N_{imp})$, where N_{imp} is the impurity concentration in the base. It could be noted the decrease of μ_H, as expected due to the scattering of the dopant atoms. At constant doping level, μ_H decreases with the increase of X_{Ge}. The error bar in determine μ_H the Hall mobility is ±15%.

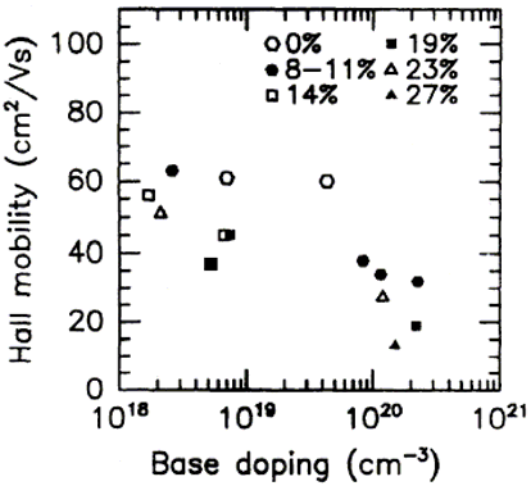

Fig.2. $\mu_H^p = f(N_{imp})$; $X_{Ge} = 0 \div 27\%$

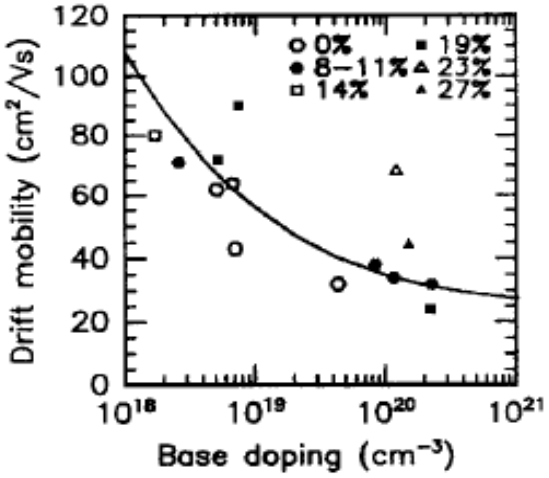

Fig.3. $\mu_d^p = f(N_{imp})$; $X_{Ge} = 0 \div 27\%$.

To determine the drift mobility μ_d^p and Hall scattering coefficient, besides the Hall measurements, measurement of carrier concentration in the base is also required. The total (integrated) concentration of holes N_{tot}^p is obtained by SIMS measurements, where full ionization of dopant atoms is accepted. The precision of μ_d^p estimation is ±25%.

Fig. 3 shows the relation $\mu_d^p = f(N_{imp})$ for $X_{Ge} = 0 \div 27\%$. Drift mobility μ_d^p decreases with increasing of doping level.

For equal doping levels a slight trend of increasing of μ_d^p with X_{Ge} at low doping levels could be noted, but this trend is smaller than the measurement error bar (±25%). McGregor et al [4] have also observed increase of μ_d^p at changes of X_{Ge} in the range $0 < X_{Ge} < 0.20$ for doping levels $1, 5 \div 2.10^{19}$ cm^{-3}.

After [13] the experimental data for μ_d^p are best described by the equation:

(5) $$\mu_d^p = 20 + 350/[1 + (N_{imp}/10^{17})^{0,5}]$$

which could be written also in the following form, similar to equation (3):

(5a) $$\mu_d^p = \mu_{pmin} + \mu_o / [1 + (N_{imp} / 2,75.\ 10^{17})^{\alpha}]$$

Where $\alpha = 0,5$; $\mu_{pmin} = const = 20$ cm²/v.s ; $\mu_o = const = 350$ cm²/v.s

The relation $\mu_d^p = f(N_{imp})$ from equation (5) is graphically presented in Fig.3 with a solid line and does not depend on X_{Ge}.

The drift hole mobility model, described in [13] allows forecast of sheet resistance R_{SB} for a random structure in a wide range of dopant and Ge concentrations.

3) Relation of the collector current in SiGe HBT from R_{SB} and narrowing of the energy gap in $Si_{1-x}Ge_x$.

Two basic parameters in dc-design of SiGe HBT are the sheet resistance of the base R_{SB} (R_{SB}=1/ (e. μ_p. G_B) and the enhancement of J_{co} compared to that in Si. R_{SB} is an important parameter in UHF applications of $Si_{1-x}Ge_x$ HBTs. The effective narrowing of the energy bandgap $\Delta E_{g\,eff}$ determines the coefficient of increase of the collector current compared to that of a Si transistor:

(6) $J_{co} = e^2. (N_c.N_\upsilon)_{SiGe} / (N_c.N_\upsilon)_{Si}$ **x** $n_{ioSi}^2. D_n.\mu_p.R_{SB}. Exp (\Delta E_{g\,eff} / kT)$

where μ_p is the lateral drift hole mobility and D_n - coefficient of vertical diffusion of electrons in the p+ base, J_{co} - saturation collector current.

Equation (6) expresses the relation between collector current (i.e. gain) and base surface resistance.

The effect of narrowing of the base at high dopant levels effects to a significantly greater degree the J_{co}, compared to the decrease of lateral and vertical drift mobility. This narrowing breaks the linearity of $J_{co} = f(N_B)$ and limits the decrease of the collector current at low R_{SB}.

ΔE_g at high doping is a little bit higher in Si, than in $Si_{1-x}Ge_x$, which means slightly lower values of J_c in a Si transistor at high doping of the base.

The relation between the narrowing of the energy bandgap and x_{Ge} is not dependent on the doping levels; at the same time the "effect" of the high doping in $\Delta E_{g\,eff}$ does not depend on X_{Ge} and it is a slightly weaker than that in Si at the same doping levels, which could be explained with the lower value of N_υ in $Si_{1-x}Ge_x$.

CONCLUSION

1) The paper discusses two hole mobility (μ_d^p and μ_H^p) (lateral mobility component) in the growth plane of $Si_{1-x}Ge_x$ layer - as parameters which determine the resistance of the active base R_B and thus - the UHF behavior of SiGe HBT.

2) The basic parameters (N_{imp}, X_{Ge}, max voltage) influencing the hole mobility are revealed

3) A detailed review of the publications dealing with μ_d^p and μ_H^p behavior related to dopant concentration and Ge content in $Si_{1-x}Ge_x$ base of HBT is performed. The conclusion based on the analysis of the data [2÷4, 7, 8, 10÷11, 13, 14] is as follows: the lateral component on the drift mobility μ_d^p (or μ_{app}^p) of the strained $Si_{1-x}Ge_x$ layers is greater than that of Si and increases as x_{Ge} increases [11, 12]. With the increasing of x_{Ge} the effective mass of holes m_{eff}^p decreases, due to the decrease of the density N_υ of the states in the valence band [3, 7, and 14]. At increase of N_{imp} from 10^{18} to 10^{20} cm^{-3}, μ_d decreases due to the increase of coulomb scattering; the same effect is

observed with the increase of the scattering potential U_o in the range $U_o = 0{,}20 \div 0{,}30$ eV

It is important to note that the summary error in μ_d determination is ±37% (typ ±25%). The difference between experimental and theoretical evaluations due to inaccuracy in SIMS evaluation of carrier concentration, ionization degree of dopant atoms, differences in evaluation of the scattering mechanism, not precise evaluation of the effect of high doped, incl. degenerating of the semiconductor. Based on the above, it's accepted that drift mobility is independent from Ge content.

4) Equations describing the relation μ_d^p, $\mu_H^p = f(N_{imp}, X_{Ge})$ (equations (3), (5)), are given, which differ as in [11, 15] μ_{pmin}, $\mu_0 = f(X_{Ge})$, and in [13] $\mu_d^p \neq f(X_{Ge})$. These relations could be used for simulation of dc-regime of SiGe HBTs.

REFERENCES

[1] J.D.Harame, M.Stork et al., Optimization of SiGe HBT Technology for High Speed Analog and Mixed Signal Applications, Int. Electron Dev. Meet. Tech. Digest.1993, pp. 71÷74.

[2] T.Manku, A.Nathan, Lattice Mobility of Holes in Strained and Unstrained $Si_{1-x}Ge_x$ Alloys, IEEE Electron Dev. Lett., vol.12, 1991, pp. 704÷706.

[3] T.Manku, McGregor, A.Nathan, D.J. Roulston et al., Drift Hole Mobility in Strained and Unstrained Doped $Si_{1-x}Ge_x$ Alloys, IEEE on ED, ED-40, 1993, pp. 1990÷1996.

[4] J.M. McGregor, T.Manku, D.J.Roulston et al., Measured in-plane Hole Drift and Hole Mobility in Heavily-Doped Strained p-Type $Si_{1-x}Ge_x$, Jour. Electron Mater., vol.22, 1993, pp.319÷321

[5] L.E.Kay, T.W.Tang, Monte Carlo Calculation of Strained and Unstrained Electron Mobility in Si_{1-x} Ge_x using un Improved Ionized Impurity Model, Jour. of Appl. Phys., vol.70, 1991, pp. 1483÷1488.

[6] R.J.E.Hueting, J.W. Slotboom et al., On the Optimization of SiGe-Base Bipolar Transistors, IEEE Trans. on ED, ED-43, 1996, pp. 1518÷1524.

[7] J.M.Hinckley, J.Singh, Hole Transport Theory in Pseudomorphic $Si_{1-x}Ge_x$ Alloys Grown on Si (001) Substrates, Phys. Rev. B, vol.41, No 5, 1990, pp. 2912÷2926.

[8] T.Manku, A.Nathan, Effective Mass for Strained p-type $Si_{1-x}Ge_x$, Jour. Appl. Phys., vol.69, No 12, 1991, pp. 8414÷ 8416.

[9] B.Peicinovič, L.E.Kay, T.V.Tang, D.H.Navon, Numerical Simulation and Comparison of Si BJTs and $Si_{1-x}Ge_x$ HBTs, IEEE trans. on ED, ED-36, No10, 1989, pp. 2129÷2137.

[10] T.Manku, A.Nathan, Electron Drift Mobility in Based on Unstrained and Strained Coherently $Si_{1-x}Ge_x$ Grown on (001) Si Substrate, IEEE on ED, ED-39, 1992, pp. 2082÷2088.

[11] T.K.Carns, S.K.Chun, M.O.Tanner et al., Hole Mobility Measurements in Heavily Doped $Si_{1-x}Ge_x$ Strained Layers, IEEE Trans. on ED, ED-41, No7, !994, pp. 1273÷1279.

[12] T.M.Kamins, K.Nauka et al., High Frequency Si/ $Si_{1-x}Ge_x$ Heterojunction Bipolar Transistors, IEEE Electron Device Letters, vol.10, 1989, pp. 503÷505.

[13] Z.Matutinović-Krstelj, V.Venkataraman, Base Resistance and Effective Bandgap Reduction in n-p-n Si/ $Si_{1-x}Ge_x$ /Si HBT's with Heavy Base Doping, IEEE Trans. on ED, ED43, No3, 1996, pp.457÷466

[14] S.K.Chun, K.L.Wang, Effective Mass and Mobility of Holes in Strained $Si_{1-x}Ge_x$ Layers on <001> $Si_{1-x}Ge_x$ Substrate, IEEE Trans. on ED, ED-39, 1992, pp. 2153÷2164.

[15] N.D.Arora, J.R.Hauser, D.J.Roulston, Electron and Hole Mobility in Silicon as a Function of Concentration and Temperature, IEEE Trans. on ED, ED-29, 1982, pp. 292÷295.