A Simple, Unified 3D Stress Model for Device Design in Stress-Enhanced Mobility Technologies

A. Kumar, K. Xiu, W. Haensch
IBM Semiconductor Research and Development Center
T.J. Watson Research Center
Yorktown Heights, NY, USA
arvkumar@us.ibm.com

R. Robison[1], M. Bajaj[2], J.B. Johnson[1], S. Furkay[1], R.Q. Williams[1]
IBM Semiconductor Research and Development Center
[1]Essex Junction, VT, USA [2]Bangalore, India

Abstract—**A simple, physical model relating 3D stress field to carrier mobility enhancement is presented. The model is valid for both holes and electrons on orientations of interest for both conventional planar and FinFET technologies, and is well-suited for efficient implementation in a TCAD environment.**

Keywords-Charge carrier mobility, stress, numerical simulation

I. Introduction

Improving channel mobility through stress engineering is a powerful method of boosting device performance [1-8]. The mobility enhancement-stress relation is usually characterized using piezoresistance coefficients [1-3], which linearize this relation and are valid for low stress levels. However, today's stress elements induce high stress levels with complex geometry [4] such that the nonlinear and 3D character of this relation becomes critical, presenting a challenge for efficient implementation in a TCAD environment. In this work we introduce a simple methodology such that the mobility dependence on stress field is expressed as a universal curve of an effective stress parameter S_{eff} that is a simple function of the diagonal components of the stress tensor. This universal behavior can be modeled with a very efficient analytic mobility calculation which supplants the need for look-up tables or a real-time self-consistent multi-band computation.

We show that these simple relations can be used for both holes and electrons. We consider the cases of current flow along <110> on (001), as in conventional planar devices, and along <$\overline{1}$10> on (110), as is important for FinFETs [7].

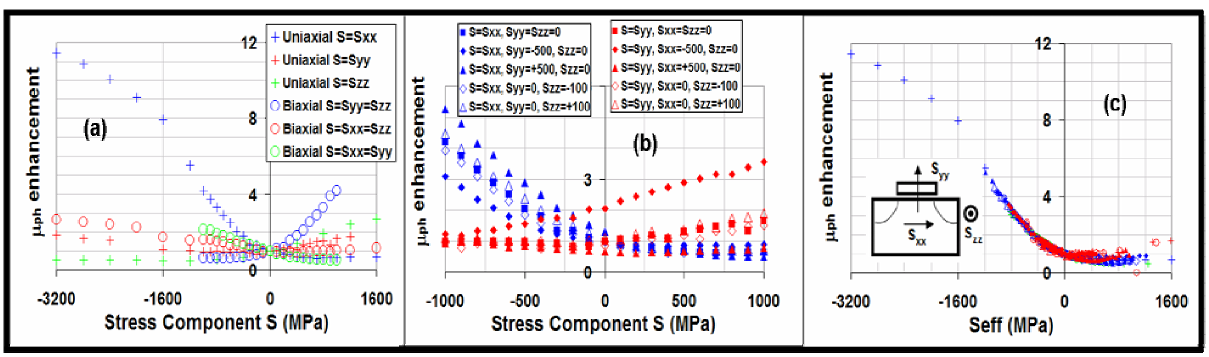

Fig. 1: (001) <110> hole phonon mobility enhancement for (a) uniaxial and biaxial stress and (b) other stress combinations as a function of the stress component varied, at vertical field F=0.5 MV/cm. In (c) all points from (a) and (b) are replotted as function of effective stress field S_{eff}. Inset shows the direction convention used in this work.

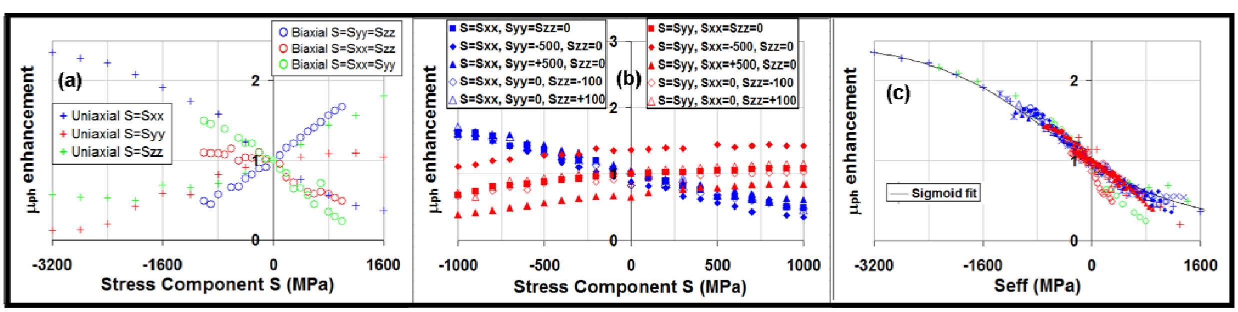

Fig. 2: (110)<$\overline{1}$10> hole phonon mobility enhancement for (a) uniaxial and biaxial stress and (b) other stress combinations as a function of the stress component varied, at vertical field F=0.5 MV/cm. In (c) all points from (a) and (b) are replotted as function of effective stress field S_{eff}.

ISBN 978-0-615-71756-2

TABLE I: Values of coefficients used in expression for S_{eff}.

	(001) <110> holes	(110) <$\bar{1}$ 10> holes	(001) <110> electrons	(110) <$\bar{1}$ 10> electrons
αx	1	1	1	1
αy	-0.4	-0.3	-1.7	0.8
αz	-0.6	-0.7	0.7	-1.8
βxx	0	0	0	0
βyy	0.00006	0.0001	0	0
βzz	0.00011	0	0	0
βxy	0	0	0	0
βyz	-0.00018	0	0	0
βxz	-0.00004	0	0	0

II. Unified Model

The basis of the Unified Model (UM) is full-band calculations [5-8] of the mobility response to a 3D stress field. To exemplify the method, Fig. 1(a) shows phonon mobility enhancement γ_{ph} for (001)<110> holes at vertical field F=0.5 MV/cm and temperature 25C for six cases of uniaxial and biaxial stress, while Fig. 1(b) shows γ_{ph} for a multitude of other cases in which one component is varied while the other two are fixed. Fig. 1(c) replots the same data in (a) and (b), but as a function of an effective stress field S_{eff}:

$$S_{eff} = \Sigma\alpha_i S_{ii} + \Sigma_{(j\geq i)}\beta_{ij}S_{ii}S_{jj} \quad . \tag{1}$$

As apparent from Table I which summarizes the coefficient values for each case, S_{eff} is approximately a linear combination of S_{xx}, S_{yy}, and S_{zz}, with small second-order terms necessary for high stress in the hole cases. Remarkably, when the mobility enhancement is plotted against this effective stress field with appropriately chosen coefficients, the data points fall on a universal curve, allowing the mobility dependence on a 3D stress field to be captured in a very simple way. Fig. 2(a-c) shows a similar analysis for (110)<$\bar{1}$ 10> holes, while Figs. 3(a-b) and 4(a-b) demonstrate that the S_{eff} concept works well for (001)<110> and (110)<$\bar{1}$ 10> electrons, respectively. Interestingly, note that (α_x+ α_y+ α_z)=0 for all cases.

We now generalize our results as a function of vertical field F. Fig. 5(a-b) shows γ_{ph} as a function of S_{eff} for (001)<110> holes and electrons, for F from 0.25 to 1 MV/cm. Again, the data points all fall on universal curves simply characterized by field-dependent coefficients. For both holes and electrons, curves of the phonon mobility enhancement γ_{ph} (relative to the unstressed phonon mobility μ_0) can be fit to a sigmoid function

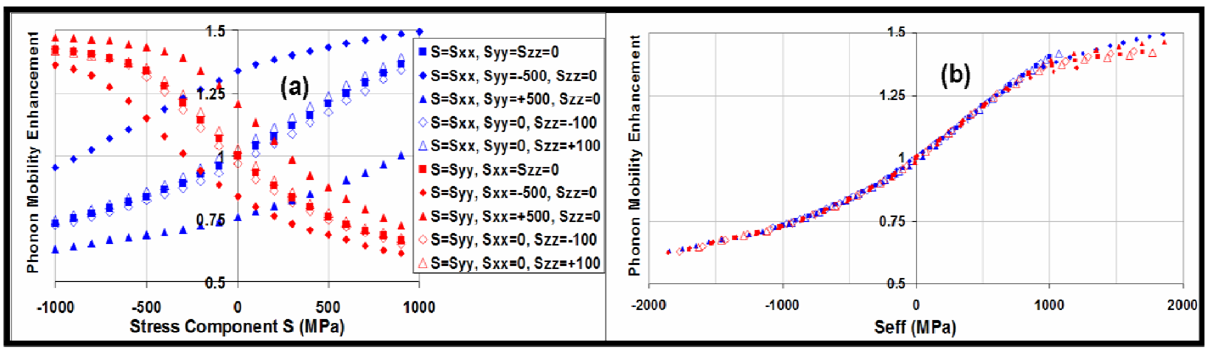

Fig. 3: (001) <110> electron phonon mobility enhancement (a) various stress combinations as a function of the stress component varied, at vertical field F=0.5 MV/cm. In (b) all points from (a) are replotted as function of S_{eff}.

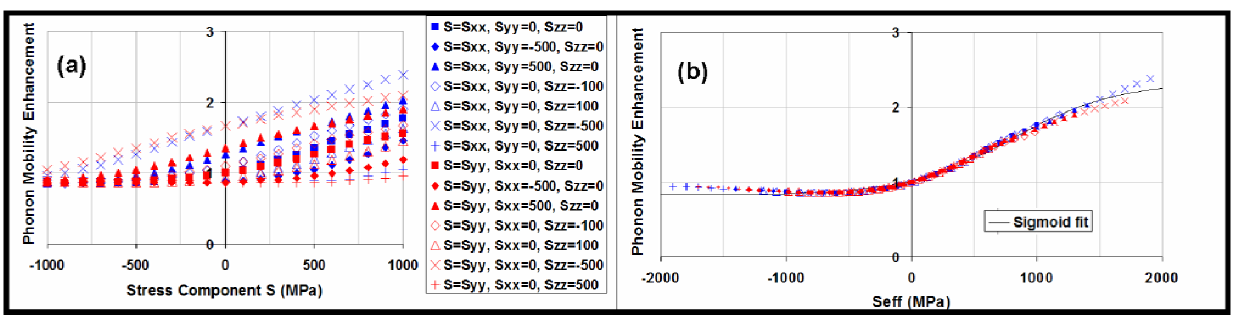

Fig. 4: (110)<$\bar{1}$ 10> electron phonon mobility enhancement (a) various stress combinations as a function of the stress component varied, at vertical field F=0.5 MV/cm. In (b) all points from (a) are replotted as function of S_{eff}.

TABLE II: Values of parameters in sigmoid fits.

	(001) <110> holes	(110) <$\bar{1}$ 10> holes	(001) <110> electrons	(110) <$\bar{1}$ 10> electrons
μ_0	212	1235	810	326
A_1	2460	$505-365F+164F^2$, $F\leq 0.5$, 364, $F\geq 0.5$	$565-81F-44F^2$	270
A_2	42	$9136-25027F+24494F^2$, $F\leq 0.5$, 2746, $F\geq 0.5$	$2028-1992F+920F^2$	761
S_0	-1338	$-2084+6879F-6896F^2$, $F\leq 0.5$, -368, $F\geq 0.5$	$1334-2646F+875F^2$	799
t	524	-650	$882-987F+604F^2$	417

$$\gamma_{ph} = (1/\mu_0)\left((A_1-A_2)/(1+\exp((S_{eff}-S_0)/t)) + A_2\right) \qquad (2)$$

with parameters for each case shown in Table II. For (001)<110> holes the field dependence is sufficiently weak [6] that field-independent coefficients are used for simplicity. For (110)<$\bar{1}$ 10> holes, field-dependent coefficients are used only below 0.5 MV/cm since the field dependence becomes significant only for low F. For (110)<$\bar{1}$ 10> electrons, the field dependence is also very weak, so we have used field-independent coefficients. Sigmoid fits for (110)<$\bar{1}$ 10> holes and electrons at F=0.5 MV/cm are shown in Figs. 2(c) and 4(b).

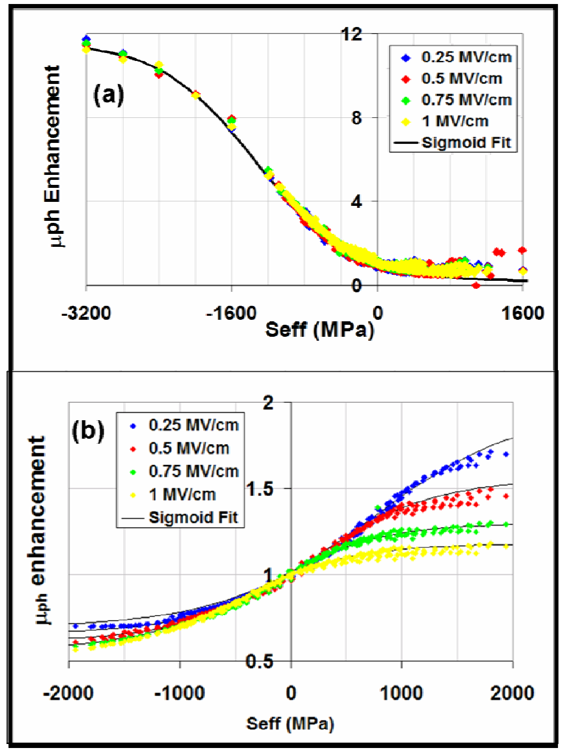

Fig. 5: Vertical field dependence for (001)<110> (a) holes and (b) electrons along with sigmoid fits.

III. IMPLEMENTATION

We have implemented the UM into the IBM continuum device simulator FIELDAY [9] by modifying the Mujtaba mobility model [10], with stress fields obtained from self-consistent process simulation**.** Conventionally a piezoresistance coefficient relates the total mobility enhancement response from a stress field [3] while the enhancement calculated here is for the phonon mobility μ_{ph} only. The phonon mobility μ_{ph} is combined with other mobility components using Matthiessen's rule to obtain the total mobility μ_T.

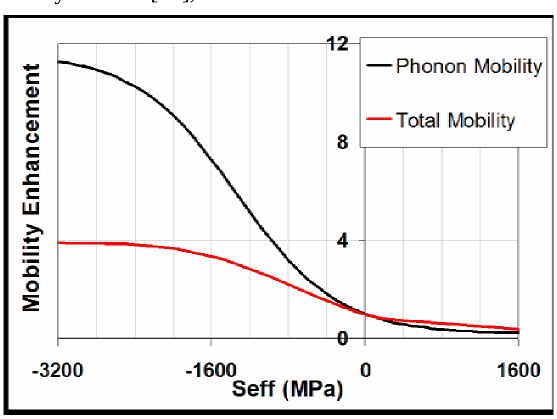

Fig. 6: Comparison of phonon vs. total mobility enhancement for (001)<110> holes.

For the case of electrons, there is an ample body of literature [11-14] which suggests reduction of surface roughness (SR) with strain. To partially account for this, we choose for electrons to apply γ_{ph} to both phonon and SR components. On the other hand, for holes unchanged [15] or increased [6] SR scattering is suggested, so that we apply γ_{ph} to μ_{ph} only and leave the other mobility components unchanged. For holes, inclusion of the unenhanced SR scattering dampens the total mobility, leading to saturation of μ_T as shown in Fig. 6. This gives results consistent with calculations for purely uniaxial compression stress (S_{yy}=S_{zz}=0) [1]. Implemented TCAD shows better agreement with 45nm hardware for both nFET and pFET using these assumptions.

IV. DISCUSSION AND CONCLUSION

These expressions not only provide a simple methodology for handling arbitrary stress fields in TCAD but also provide intuitive formulas useful for stress engineering by indicating favorable directions for each type of stress. For example, the large negative α_z for (110)$\langle\bar{1}10\rangle$ electrons suggests transverse compressive strain to improve electron mobility in a FinFET configuration favorable for hole mobility [7].

In conclusion, we have developed a simple but powerful physically-based TCAD tool for stress engineering device design in future technologies. The model allows for arbitrary stress fields, thereby providing a unifying expression for uniaxial and biaxial stress. It extends the low-stress limit of piezoresistance coefficents to the high-stress regime required for current technologies. Dependence on vertical field is included, while generalization to account for temperature dependence is among the problems we have left for future work. Finally, the model allows for both holes and electrons under different orientations, making it a very versatile tool for predictive simulation in future technology nodes.

ACKNOWLEDGMENT

This work was performed by the Research Alliance Teams at various IBM Research and Development Facilities. The authors thank E. Nowak for helpful discussions.

REFERENCES

[1] S. Thompson, G. Sun, Y. Choi, and T. Nishida, "Uniaxial-process-induced strained-Si: extending the CMOS roadmap," *IEEE Trans. Electron Devices*, vol. 53, no. 5, pp. 1010-1020, May 2006.

[2] S. Suthram, J. Ziegert, T. Nishida, and S. Thompson, "Piezoresistance coefficients of (100) silicon nMOSFETs measured at low and high (~1.5 GPa) channel stress," *IEEE Elec. Dev. Lett*., vol. 28, no. 1, pp. 58-62, Jan. 2007.

[3] C. S. Smith, "Piezoresistance effect in germanium and silicon," *Phys. Rev.*, vol. 94, no. 62, pp. 42-49, 1954.

[4] F. Payet, F. Boeuf, C. Ortolland, and T. Skotnicki, "Nonuniform mobility-enhancement techniques and their impact on device performance," *IEEE Trans. Electron Devices*, vol. 55, no. 4, pp. 1050-1057, Apr. 2008.

[5] M. Fischetti, Z. Ren, P. Solomon, M. Yang, and K. Rim, "Six-band k.p calculation of the hole mobility in silicon inversion layers: Dependence on surface orientation, strain, and silicon thickness," *J. Appl. Phys.*, vol. 94, no. 2, pp. 1079-1095, Jul. 2003.

[6] G. Sun, Y. Sun, T. Nishida, and S. Thompson, "Hole mobility in silicon inversion layers: stress and surface orientation," *J. Appl. Phys.*, vol. 102, no. 8, pp. 084501-084508, Oct. 2007.

[7] P. Packan *et al.*, "High performance hi-K + metal gate strain enhanced transistors on (110) silicon," in *IEDM Tech. Dig*., 2008.

[8] F. Bufler, A. Erlebach, and M. Oulmane, "Hole mobility model with silicon inversion layer symmetry and stress-dependent piezoconductance coefficients," *IEEE Electron Device Lett*.., vol. 30, no. 9, pp. 996-998, Sep. 2009.

[9] M. Ieong and P. Oldiges, "Technology modeling for emerging SOI devices," in *Proc. SISPAD*, pp. 225-230, 2002.

[10] S. Mujtaba, R. Dutton, and D. Scharfetter, "Semi-empirical local NMOS mobility model for 2-D device simulation incorporating screened minority impurity scattering," in *Proc. NUPAD*, pp. 3-6, 1994.

[11] M. Fischetti, P. Gamiz, and W. Haensch, "On the enhanced electron mobility in strained silicon inversion layers," *J. Appl. Phys.*, vol. 92, no. 12, pp. 7320-7324, Dec. 2002.

[12] M. Borici, J. Watling, R. Wilkins, L. Yang, J. Barker, and A. Asenov, "Interface roughness scattering and its impact on electron transport in relaxed and strained Si n-MOSFETs," *Semicon. Sci. Tech*., vol. 19, no. 4, pp. S155-S157, 2002.

[13] G. Hadjisavvas, L. Tsetseris, and S. Pantelides, "The Origin of Electron Mobility Enhancement in Strained MOSFETs," *Elec. Dev. Lett.*, vol. 28, no. 11, pp. 1018-1020, Nov. 2007.

[14] Y. Zhao, M. Takenaka, and S. Takagi, "On Surface Roughness Scattering-Limited Mobilities of Electrons and Holes in Biaxially Tensile-Strained Si MOSFETs," *IEEE Electron Device Lett.*, vol. 30, no. 9, pp. 996-998, Sep. 2009.

[15] X. Yang, S. Parthsarathy, Y. Sun, A. Koehler, T. Nishida, and S. Thompson, "Temperature dependence of enhanced hole mobility in uniaxial strained *p*-channel metal-oxide-semiconductor field-effect transistors and insight into the physical mechanisms," *Appl. Phys. Lett.*, vol. 93, no. 24, pp. 243503-243505, Dec. 2008.