STAND-ALONE PROJECT - FINAL REPORT

P19997-N14 **Project number**

Project title **Electron Mobility Enhancement in Strained Silicon**

Project leader O.Univ.Prof.Dipl.-Ing.Dr. Siegfried SELBERHERR

1. Summary for public relations work

English version:

The rapid increase in computational power and speed of integrated circuits is supported by the aggressive size reduction of semiconductor devices. With scaling apparently approaching its fundamental limits, the semiconductor industry is facing critical challenges. New engineering solutions and innovative techniques are required to improve CMOS device performance. Stress induced mobility enhancement is the most attractive solution to increase the device speed and certainly takes a key position among other technological changes for the new technology generations. In addition, novel device architectures based on multi-gate structures with better electrostatic channel control and reduced short channel effects are developed. A comprehensive analysis of transport in multi-gate MOSFETs under general stress conditions is required for analyzing the enhancement of device performance. Besides the biaxial stress obtained by epitaxially growing silicon on a silicon-germanium substrate, modern techniques allow the generation of large uniaxial stress along the [110] channel. Stress in this direction induces significant shear lattice distortion. The influence of the shear distortion on the conduction band structure has not yet been carefully analyzed.

In this project the modification of the conduction band structure due to the shear stress has been theoretically investigated. A perturbation expansion of the Hamiltonian for the deformed lattice was derived. Based on this expansion, analytical expressions for the relative shift between the conduction band valleys and the effective mass change due to the shear stress components were obtained. Results of analytical calculations for the band structure have been verified against results obtained by the empirical pseudo-potential calculations and density-functional calculations (performed with VASP). The conductivity mass in the lowest valleys decreases along the [110] direction of tensile stress providing significant mobility enhancement. Analytical expressions for the band structure of strained silicon have been embedded into an existing Monte Carlo transport simulator. Accurate transport modeling in bulk silicon, in surface inversion layers, and thin silicon films for general strain conditions and arbitrary substrate orientations has been performed. The analytical band structure model enables efficient simulations of conventional and future multi-gate MOSFET architectures and allows the optimization of MOSFET performance under general stress conditions.

German version:

Die rasche Steigerung der Rechenleistung und Geschwindigkeit von integrierten Schaltkreisen wird unterstützt durch die aggressive Größenreduktion der Halbleiterbauelemente. Das nahende Ende der Bauteilskalierung, durch Erreichen fundamentaler physikalischer Grenzen, stellt die Halbleiterindustrie vor kritische Herausforderungen. Neue konstruktive Lösungen und innovative Techniken werden benötigt, um die Leistung von CMOS-Transistoren weiter zu steigern. Durch mechanische Verspannung induzierte Beweglichkeitsserhöhung stellt die attraktivste Möglichkeit dar, die Bauteilgeschwindikeit zu erhöhen und nimmt eine Schlüsselposition unter den möglichen technischen Verbesserungen für zukünftige Technologiegenerationen ein. Zusätzlich werden neue Bauteilarchitekturen basierend auf Multi-Gate-Strukturen mit besserer elektrostatischer Kontrolle und reduzierten Kurzkanaleffekten entwickelt. Eine umfassende Analyse des Ladungstransportes in Multi-Gate-MOSFETs unter beliebigen Verspannungen wird benötigt, um die Leistungssteigerung dieser Bauteile zu verstehen. Neben der biaxialen Verspannung, erzielt durch epitaxial aufgewachsenes Silizium auf einem Silizum-Germanium Substrat, erlauben aktuelle Techniken große uniaxiale Verspannungen entlang des [110]-Kanals. Verspannungen entlang dieser Richtung generieren signifikante Schergitterverzerrungen. Der Einfluss dieser Scherverformung auf die Bandstruktur des Leitungsbandes wurde bisher noch nicht sorgfältig analysiert.

In diesem Projekt wurde die Modifikation des Leitungsbandes unter Scherspannung mit Hilfe theoretischer Mittel erforscht. Ein Hamilton-Operator für das verformte Gitter, basierend auf der Entwicklung nach kleinen Störungen, wurde abgeleitet. Ausgehend von dieser Entwicklung wurden analytische Ausdrücke für die relative Verschiebung zwischen den Leitungsbandtälern und der effektiven Massenänderung durch die Scherspannungskomponente abgeleitet. Die Ergebnisse des analytischen Models für die Bandstruktur wurden durch Vergleich mit der Bandstruktur aus empirischen Pseudopotentialberechnungen verifiziert. Die effektive Leitungsbandmasse in den Tälern mit geringster Energie verringert sich entlang der [110]-Richtung unter tensiler Verspannung und stellt damit eine signifikante Erhöhung der Beweglichkeit bereit. Die entsprechenden analytischen Ausdrücke wurden in einen bestehenden auf der Monte Carlo-Methode basierenden Transportsimulator implementiert. Die präzise Transportmodellierung in Bulksilizium, in Oberflächeninversionsschichten und dünnen Siliziumschichten für beliebige Verspannungen als auch Substratorientierungen wurde damit gezeigt. Das analytische Bandstrukturmodel erlaubt eine effiziente Simulation von sowohl konventionellen als auch zukünftigen Multi-Gate-MOSFET-Architekturen und ermöglicht die weitere Optimierung der Leistungsfähigkeit von MOSFETs für allgemeine Verspannungsbedingungen.

2. Brief project report

2.1 Report on the scientific work

2.1.1 Information on the development of the research work

In this project Si band structure calculations under arbitrary strain conditions including shear strain were carried out. Based on a comprehensive analysis of strain-induced changes in the conduction band structure and consequent modification of scattering rates, accurate transport modeling in bulk Si and thin-body Si films for general strain conditions and arbitrary substrate orientations was performed. The applications were mainly focused on the optimization of stress, substrate orientation, and current direction conditions for performance enhancement of advanced bulk and multi-gate MOSFETs.

The project was divided into four parts. In the first step the empirical pseudo-potential method was used to calculate the band structure of Si for arbitrary stress conditions. Theoretical investigations of the conduction band modification due to shear strain based on a perturbative expansion of the Hamiltonian of the deformed lattice were performed. This allowed a derivation of analytical expressions for the valley splitting, effective masses modifications, and the non-parabolicity parameter dependence on the shear stress component. In the second step the substantial change in the band structure due to shear strain and the modifications in the scattering rates were investigated. The third step consisted of implementing the electron-phonon and surface roughness scattering rates, modified due to the stress, in the multi-purpose Monte Carlo simulator, Vienna Monte Carlo (VMC), developed at the Institute for Microelectronics. In the last step the VMC simulator was used to analyze the influence of general stress conditions on transport in bulk Si. Both electron and hole mobilities in bulk Si were evaluated using full-band Monte Carlo simulations with the band structure obtained numerically from the empirical pseudo-potential method. Impact ionization was introduced in order to correctly reproduce mobility at high driving fields. Results of full-band simulations were compared with the results obtained with the analytical band structure description for arbitrary stress. Comparisons with the mobility models based on the piezoresistance coefficients were performed. The upper limit for stress for which Monte Carlo simulations with analytical band structure reproduce reasonably well the more accurate results of the full-band Monte Carlo simulations were determined for general stress conditions. The region of applicability of an analytical band structure and a piezoresistance coefficient model for transport in bulk Si is thereby determined.

2.1.2 Most important results and brief description of their significance

In the first year an efficient two-band k.p model which accurately describes the six lowest conduction band valleys in silicon was developed. A perturbative expansion of the k.p Hamiltonian with respect to stress was obtained. Close to the Brillouin zone edge at the X-point only the two lowest conduction bands, which are degenerate exactly at the X-point, can be considered. A degenerate k.p perturbation theory for these two lowest conduction bands was developed. The model is consistent with the point group symmetry at the X-point. The model includes both diagonal and off-diagonal components of the strain tensor.

The main findings are

1. By comparing the two-band analytical k.p model to the results of the empirical pseudo-potential calculations and for the conduction band structure, it was demonstrated that the model reproduces well the dispersion in the lowest conduction band up to energies of 0.5-0.8eV, for arbitrary stress conditions;

2. Off-diagonal strain components due to shear stress lead to a profound modification of the band structure resulting in:

- valley shift dependence on strain,
- valley minimum position dependence on strain,
- transversal mass dependence on strain,
- longitudinal mass dependence on strain, and
- strain-dependent non-parabolicity.

3. Analytical dependences for the above mentioned characteristics on shear strain are in excellent agreement with the numerically obtained dependences obtained from the empirical pseudo-potential calculations. At high [110] uniaxial stress values, a slight dependence on shear strain dependence of the shear deformation potential must be taken into consideration in order to reproduce accurately the strain dependence of the transversal effective masses. This dependence can be obtained form higher order terms of the perturbative expansion of the Hamiltonian from the empirical pseudo-potential band structure calculations.

4. Preliminary analyses with the two-band k.p model of the subband structure in thin silicon films showed that the subband parameters depend on the film thickness. A pronounced modification of the conductivity mass of primed subbands in thin films was predicted. For unprimed subbands, the non-parabolicity parameter shows also a dependence on the film thickness.

5. Stress-induced mobility enhancement in Si has become a key technique to increase performance of modern CMOS devices, and the strain-dependent effective mass provides an additional cause for the mobility enhancement. The mobility enhancement in thin films was analyzed by including the electron-phonon and surface roughness scattering rates, for bulk dependences of the transversal masses on shear strain. The thickness dependence of the non-parabolicity modifies the density of states, which results in enhanced scattering. It is demonstrated that the enhancement of the low-field mobility in uniaxially stressed UTB FETs is partly hampered by an increase in non-parabolicity at higher stress.

During the second year we have been successfully exploring the developed two-band k.p model for the conduction band in silicon to obtain an accurate subband structure and wave functions in confined silicon systems. The wave functions and the subband energies are used to evaluate the scattering rates which are employed in the low-field mobility calculations. Special attention has been paid to the numerical implementation of the two-band k.p solver which computes the wave functions and eigenenergies self-consistently.

1. We have further justified the two-band k.p model by comparing its predictions to the results of first-principle density-functional band structure calculation performed with the Vienna Ab-initio Simulation Package (VASP) and obtained excellent agreement.

2. The two-band k.p model demonstrates that the subband parameters are functions of shear strain and film thickness. It was shown that the subband quantization energies' dependence on shear strain is due to the strain dependent valley shift and the dependence of the quantization mass on shear strain.

3. The two-band k.p model allows explaining the experimentally observed splitting in the perpendicular magnetic field between the two unprimed subbands with the same principal quantum number, which are usually considered to be degenerate and thus completely equivalent.

4. It was also shown that the splitting between these "equivalent" subbands can be considerably enhanced by the shear strain.

5. It has been demonstrated that self-consistent calculations of the subband structure can be efficiently performed within the numerical solver based on the two-band k.p model.

6. An efficient Monte Carlo algorithm to evaluate the low-field mobility including degeneracy effects in strained devices was developed. The algorithm uses the scattering rates computed with help of the subband wave functions. The algorithm is used to evaluate transport in ultra-scaled MOSFETs. Possible applications to bio-sensors have also been considered.

During the final year a comprehensive analysis of electron mobility enhancement in surface layers and ultra-thin body multi-gate MOSFETs for different substrate orientations under general strain conditions was performed.

1. It was demonstrated that the unprimed subbands in unstrained thin silicon films are not equivalent, but develop different dispersions along the [110] direction. The dependence of the curvature effective mass of the unprimed subbands along the [110] direction on strain and film thickness was obtained.

2. The decrease of the effective masses along the [110] direction of tensile strain is the reason of the [110] mobility enhancement in ultra-thin films. Due to an additional strain- and thickness dependent inter-subband splitting the higher subband with unfavorable masses becomes depopulated, prompting for an additional mobility enhancement in thin (001) films.

3. Subband parameters in strained (-110) silicon films were evaluated. It is shown that tensile uniaxial stress along the [110] channel direction alters the relative position of primed and unprimed subband ladders in (-110) oriented silicon films. The effective mass of the lowest subband in the transport direction is reduced with increased stress and decreased thickness.

4. MOSFETs with ultra-thin body tensely stressed along the [110] channel have superior transport characteristics over [010] FinFETs because of the subband ladders' inversion and a lighter effective mass of the lowest subband.

5. A multi-subband Monte Carlo method designed for small signal analysis was choosen to evaluate the mobility in MOSFETs with a thin silicon body. An advantage of the method is that it includes degeneracy effects due to the Pauli exclusion principle, which are important for mobility calculations in ultra-thin films, especially at high carrier concentrations. The multi-subband method uses the subband wave functions and subband energies obtained with help of a two-band k.p model. The wave functions are employed to evaluate the scattering rates with phonons and surface roughness. The surface roughness at the two thin film interfaces is assumed to be equal and uncorrelated. It was demonstrated that the decrease of the effective masses in [110] direction induced by shear strain becomes more pronounced with the film thickness reduced, guaranteeing the mobility enhancement even in ultra-thin films.

6. The calculated subband parameters were used to evaluate transport in a ballistic n-channel MOSFET, which is considered as the ultimate limit of scaling. It was demonstrated that an on-current enhancement of nearly 50% can be achieved at high stress values. Applications to MOSFET-based future bio-sensors were also considered.

7. The strain-induced mobility enhancement and drive current increase combined with the improved channel control makes multi-gate MOSFETs based on thin films or silicon fins preeminent candidates for the 22nm technology node and beyond.

In summary, the main goals of the project are achieved in agreement with the anticipated timeline.

2.1.3 Information on the running of the project

The complete duration of the project was 36 months. The project team consisted of Dr. Viktor Sverdlov and Dipl.-Ing Thomas Windbacher. The literature study was carried out by Dr. Sverdlov. He also developed the two-band k.p Hamiltonian and focused on the theoretical background. Dipl.-Ing. Thomas Windbacher concentrated on the numerical solution of the analytical two-band k.p model and also on a possible application in the field of biologically sensitive field-effect transistors. Dr. Viktor Sverdlov took care of the implementation of the developed models into the Institute's Monte Carlo simulator. The software components were gradually developed and each step was concluded by carrying out extensive tests to ensure the physical plausibility of the models. The tests were carried out by all members of the team and led to many fruitful discussions about the simulation results and various aspects of physics, numerical algorithms, and software design.

During the project all members regularly published and presented their results at international conferences and in scientific journals.

2.2. Personnel development

The knowledge and experience gained during the FWF project serves as an excellent basis for further scientific work and personal development for all project members. Dr. Viktor Sverdlov had the opportunity to obtain valuable experience in organizing research work on the complex problem of strain-enhanced transport in MOSFETs, requiring time and personal management. Thanks to the scientific results obtained he is planning to complete his habilitation during the next semester. All members benefited from the great opportunity to develop and improve their strategies for publishing obtained results and from the communication with the scientific community. Dipl.-Ing. Thomas Windbacher, as a doctoral student during the project, had the opportunity to gain deeper understanding in the underlying theoretical physics and to improve his skills in solving the related numerical problems. He also gained knowledge in the commencing field of biologically sensitive field-effect transistors, while studying the promising application of stress in these devices.

2.3 Effects of the project outside the scientific field

Dr. Sverdlov presented his working field, summarized as "Re-Inventing the Transistor: Moore's Law in Action", at the Fakultätskolloquium at TU Wien on the 12th of May 2010.

3. Information on project participants

not funded by the FWF			**funded by the FWF (project)**		
co-workers	**number**	**Person-months**	**co-workers**	**Number**	**Person - months**
non-scientific co-workers			non-scientific co-workers		
diploma students			diploma students		
PhD students			PhD students	1	36
post-doctoral co-workers			post-doctoral co-workers	1	36
co-workers with “Habilitation” (professorial qualifications)			co-workers with “Habilitation” (professorial qualifications)		
professors	1	6	professors		

4. Attachments

List 1

1.a. scientific publications

1.a.1. Peer-reviewed publications (journals, contribution to anthologies, working papers, proceedings etc.)

1) T. Windbacher, V. Sverdlov, O. Baumgartner, S. Selberherr: "Electron Subband Structure in Strained Silicon UTB Films from the Hensel-Hasegawa-Nakayama Model - Part 1 Analytical Consideration and Strain-Induced Valley Splitting"; *Solid-State Electronics*, 54 (2010), 137 - 142.

2) V. Sverdlov, O. Baumgartner, T. Windbacher, S. Selberherr: "Modeling of Modern MOSFETs with Strain"; *Journal of Computational Electronics* (invited), 8 (2009), 3-4; 192 - 208.

3) V. Sverdlov, T. Windbacher, F. Schanovsky, S. Selberherr: "Mobility Modeling in Advanced MOSFETs with Ultra-Thin Silicon Body under Stress"; *Journal Integrated Circuits and Systems*, 4 (2009), 2; 55 - 60.

4) V. Sverdlov, G. Karlowatz, S. Dhar, H. Kosina, S. Selberherr: "Two-Band k.p Model for the Conduction Band in Silicon: Impact of Strain and Confinement on Band Structure and Mobility"; *Solid-State Electronics*, 52 (2008), 1563 - 1568.

5) V. Sverdlov, H. Kosina, S. Selberherr: "Electron Subband Dispersions in Ultra-Thin Silicon Films from a Two-Band k·p Theory"; *Journal of Computational Electronics*, 7 (2008), 3; 164 - 167.

6) V. Sverdlov, E. Ungersböck, H. Kosina, S. Selberherr: "Current Transport Models for Nanoscale Semiconductor Devices"; *Materials Science and Engineering R*, 58 (2008), 6-7; 228 - 270.

1.a.2. Non peer-reviewed publications (journals, contribution to anthologies research reports, working papers, proceedings, etc.)

1.a.3. Stand-alone publications (monographies, anthologies)

1) V.Sverdlov, “Strain-Induced Effects in Advanced MOSFETs”; in: "Computational Microelectronics", Springer-Verlag, ISBN: 978-3-7091-0381-4, approx. 250 pages. 70 illus. Hardcover, (published on 13.10.2010)

2) M. Vasicek, V. Sverdlov, J. Cervenka, T. Grasser, H. Kosina, S. Selberherr, “Transport in Nanostructures: A Comparative Analysis Using Monte Carlo Simulation, the Spherical Harmonic Method, and Higher Moments Models”; in: “Large-Scale Scientific Computing”, Springer-Verlag, 2010, ISBN: 978-3-642-12534-8, 443 – 450.

3) T. Windbacher, V. Sverdlov, S. Selberherr: "Biotin-Streptavidin Sensitive BioFETs and Their Properties"; in: "Biomedical Engineering Systems and Technologies", Springer-Verlag, 2010, ISBN: 978-3-642-11720-6, 85 - 95.

4) V. Sverdlov, O. Baumgartner, T. Windbacher, S. Selberherr: "Silicon for Spintronic Applications: Strain-Enhanced Valley Splitting"; in: "Future Trends in Microelectronics", John Wiley & Sons, 2010, ISBN: 978-0-470-55137-0, 281-291.

1.b. publications for the general public and other publications

List 2 project-related participation in international scientific conferences

2.1. Conference participations - invited lectures

1) V. Sverdlov, O. Baumgartner, T. Windbacher, S. Selberherr: "Modeling Techniques for Strained CMOS Technology"; *ULSI Process Integration*, in: "Proceedings of the 216th Meeting of the Electrochemical Society", (2009), ISBN: 978-1-56677-744-5; 3 - 18.

2) V. Sverdlov, O. Baumgartner, T. Windbacher, F. Schanovsky, S. Selberherr: "Impact of Confinement of Semiconductor and Band Engineering on Future Device Performance"; in: "Proceedings 215th Meeting of the Electrochemical Society, Silicon-on-Insulator Technology and Devices", 19/4 (2009), ISBN: 978-1-56677-712-4; 15 - 26.

2.2. Conference participations - lectures

1) V. Sverdlov, O. Baumgartner, S. Selberherr: "Subband Parameters in Strained (110) Silicon Films from the Hensel-Hasegawa-Nakayama Model of the Conduction Band"; in: "Proceedings of the International Semiconductor Device Research Symposium (ISDRS)", (2009), ISBN: 978-1-4244-6031-1; TP6-03.1 - 2.

2) V. Sverdlov, O. Baumgartner, T. Windbacher, F. Schanovsky, S. Selberherr: "Thickness Dependence of the Effective Masses in a Strained Thin Silicon Film"; in: "Proceedings of the International Conference on Simulation of Semiconductor Processes and Devices", (2009), ISBN: 978-1-4244-3947-8; 51 - 54.

3) V. Sverdlov, O. Baumgartner, T. Windbacher, F. Schanovsky, S. Selberherr: "Impact of Confinement and Stress on the Subband Parameters in Ultra-Thin Silicon Films"; in: "Proceedings Intl.Symposium on Microelectronics Technology and Devices (SBMicro)", (2009), ISBN: 978-1-56677-737-7; 389 - 396.

4) V. Sverdlov, O. Baumgartner, S. Tyaginov, T. Windbacher, S. Selberherr: "Subband Structure in Ultra-Thin Silicon Films"; in: "Proceedings of the International Symposium NANOSTRUCTURES: Physics and Technology", (2009), 62 - 63.

5) V. Sverdlov, O. Baumgartner, T. Windbacher, S. Selberherr: "Perspectives of Silicon for Future Spintronic Applications from the Peculiarities of the Subband Structure in Ultra-Thin Films"; in: "Proceedings of 2009 Silicon Nanoelectronics Workshop", (2009), 95 - 96.

6) V. Sverdlov, O. Baumgartner, H. Kosina, S. Selberherr, F. Schanovsky, D. Esseni: "The Linear Combination of Bulk Bands-Method for Electron and Hole Subband Calculations in Strained Silicon Films and Surface Layers"; in: "13th International Workshop on Computational Electronics", (2009), 49 – 52.

7) V. Sverdlov, S. Selberherr: "Mobility Modeling in Advanced MOSFETs with Ultra-Thin Silicon Body under Stress"; in: "Proceedings Intl.Symposium on Microelectronics Technology and Devices (SBMicro)", (2008), ISBN: 978-1-56677-646-2; 159 - 168.

8) V. Sverdlov, S. Selberherr: "Strain-Controlled Valley Splitting in Si-SiGe Heterostructures"; *International SiGe Technology and Device Meeting (ISTDM)*, in: "Abstract Book", (2008), 20 – 21.

9) V. Sverdlov, T. Windbacher, H. Kosina, S. Selberherr: "Stress-Induced Valley Splitting in Silicon Thin Films"; in: "Proceedings of the 9th International Conference on Ultimate Integration on Silicon", (2008), ISBN: 978-1-4244-1730-8; 93 - 96.

10) V. Sverdlov, H. Kosina, S. Selberherr: "Electron Subband Structure and Controlled Valley Splitting in Silicon Thin-Body SOI FETs: Two-Band k.p Theory and Beyond"; in: "Proceedings of the 4th Workshop of the Thematic Network on Silicon on Insulator Technology, Devices and Circuits", (2008), 41 – 42.

11) V. Sverdlov, G. Karlowatz, S. Dhar, H. Kosina, S. Selberherr: "Two-Band k·p Model for the Conduction Band in Silicon: Impact of Strain and Confinement on Band Structure and Mobility"; in: "2007 International Semiconductor Device Research Symposium", (2007), ISBN: 978-1-4244-1892-3; 2 pages.

12) V. Sverdlov, G. Karlowatz, H. Kosina, S. Selberherr: "Two-Band k.p Model for the Conduction Band in Silicon"; in: "Proceedings European Simulation and Modeling Conference", (2007), ISBN: 978-90-77381-36-6; 220 - 224.

13) V. Sverdlov, H. Kosina, S. Selberherr: "Comparative Analysis of Pseudo-Potential and Tight-Binding Band Structure Calculations with an Analytical Two-Band k·p Model: Conduction Band of Silicon"; in: "International Conference "Micro and Nanoelectronics - 2007" Book of Abstracts", (2007).

14) V. Sverdlov, H. Kosina, S. Selberherr: "Conduction Band in Silicon: Numerical Versus Analytical Two-Band k·p Model"; in: "8th Conference of the Society for Electronics, Telecommunications, Automatics, and Informatics", (2007), 4 pages.

15) V. Sverdlov, E. Ungersböck, H. Kosina, S. Selberherr: "Effects of Shear Strain on the Conduction Band in Silicon: An Efficient Two-Band k.p Theory"; in: "European Solid-State Device Research Conference", (2007), ISBN: 1-4244-1124-6; 386 - 389.

2.3. Conference participations - posters

1) O. Baumgartner, V. Sverdlov, H. Kosina, S. Selberherr: "Strain-Induced Valley Splitting in Slightly Misaligned Silicon Films"; in: "Conference Proceedings of the Sixth Workshop of the Thematic Network on Silicon-On-Insulator Technology, Devices and Circuits", (2010), 91 - 92.

2) V. Sverdlov, O. Baumgartner, T. Windbacher, F. Schanovski, S. Selberherr: "Mobility Enhanced by Shear Strain Splitting of Unprimed Subbands in (001) Silicon Films and Point Contacts"; in: "Abstracts of the International Conference on Spintronics and Quantum Information Technology (SPINTECH)", (2009), 301.

3) V. Sverdlov, T. Windbacher, O. Baumgartner, F. Schanovsky, S. Selberherr: "Valley Splitting in Thin Silicon Films from a Two-Band k·p Model"; in: "Proceedings of the 10th International Conference on Ultimate Integration of Silicon", (2009), 277 - 280.

4) T. Windbacher, V. Sverdlov, S. Selberherr: "Modeling of Low Concentrated Buffer DNA Detection with Suspend Gate Field-Effect Transistors (SGFET)"; in: "13th International Workshop on Computational Electronics", (2009), 169 - 172.

5) V. Sverdlov, T. Windbacher, O. Baumgartner, S. Selberherr: "Electron Subband Structure and Valley Splitting in Silicon Ultra-Thin Body SOI Structures from thr Two-Band k·p Model"; "; in: "Proceedings of the 5th Workshop of the Thematic Network on Silicon on Insulator Technology, Devices and Circuits", (2009), 81 – 82.

6) V. Sverdlov, T. Windbacher, S. Selberherr: "Mobility Enhancement in Thin Silicon Films: Strain and Thickness Dependences of the Effective Masses and Non-Parabolicity Parameter"; in: "International Conference on Simulation of Semiconductor Processes and Devices 2008", (2008), ISBN: 978-1-4244-1753-7; 145 – 148.

2.4. Conference participations – other

List 3 Development of collaborations

Indication of the most important collaborations (maximum 5), that took place (initiated or continued) in collaboration please give the name of the collaboration partner (name, title, institution) and a few words about the scientific content. Please also assign one of the following **categories** to each collaboration:

N			Nature **N** (national); **E** (European); **I** (other international cooperation)
	E		Extent **E1** **low** (e.g. no joint publications but mention in acknowledgements or similar); **E2** **medium** (collaboration e.g. with occasional joint publications, exchange of materials or similar but no longer-term exchange of personnel); **E3** **high** (extensive collaboration with mutual hosting of group members for research stays, regular joint publications etc.)
		D	Discipline **D** within the discipline **T** transdisciplinary

N	**E**	**D**	**Collaboration partner / content of the collaboration**
			1) Name: Title: Institution: Content:
			2) Name: Title: Institution: Content:
			3) Name: Title: Institution: Content:
			4) Name: Title: Institution: Content:
			5) Name: Title: Institution: Content:

Note: general scientific contacts and occasional meetings should not be considered as collaborations in the above sense.

List 4 “Habilitations” (professorial qualifications) / PhD theses / diploma theses

with an indication of the status (in progress / completed)

4.1. Professorial Qualifications

The work perfomed in this project is a part a Habilitation thesis of Dr. Sverdlov.

4.2. PhD Theses

During the project period Thomas Windbacher completed his doctoral thesis “Engineering Gate Stacks for Field-Effect Transistors’.

4.3. Diploma Theses

List 5 Effects of the project outside the scientific field (where appropriate)

Sections of the list:

5.1. Organization of scientific events

5.2. Particular honours, prizes etc.

5.3. Information on results relevant to commercial applications

5.4. Other effects beyond the scientific field

5.5. Relevance of the project in the organization of the relevant scientific discipline

List 6. Applications for follow-up projects

6.1 Applications for follow-up projects (FWF projects)

6.2 Applications for follow-up projects (Other national projects)

6.3 Applications for follow-up projects (International projects)