CARRIER TUNNELING IN HIGH FREQUENCY ELECTRIC FIELDS

S.D. GANICHEV[1,2], E. ZIEMANN, H. KETTERL, W. PRETTL
[1] *Institut für Experimentelle und Angewandte Physik, Universität Regensburg, 93040 Regensburg, Germany*

I.N. YASSIEVICH, V.I. PEREL
[2] *A.F. Ioffe Physicotechnical Institute, Russian Academy of the Sciences, 194021 St. Petersburg, Russia*

I. WILKE, E.E. HALLER
Materials Sciences Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA 94720, USA

An analysis is made of the ionization of deep impurity centers by high–intensity terahertz radiation, with photon energies tens of times lower than the impurity ionization energy. Under these conditions, ionization can be described as phonon–assisted tunneling in which carrier emission is accompanied by defect tunneling in configuration space and electron tunneling in the electric field of the radiation. Within a broad range of intensity, wavelength and temperature, the terahertz electric field of the radiation acts like a static field. For very high frequencies an enhancement of tunneling as compared to static fields has been observed. The transition between the quasi–static and the high frequency regime is determined by the tunneling time. For the case of deep impurities this is the time of redistribution of the defect vibrational system which depends strongly on temperature and the impurity structure. A theory of tunneling ionization of deep impurities by high frequency fields has been developed taking into account both tunneling processes.

1 Introduction

The effect of high frequency coherent radiation on tunneling in semiconductor superlattices and nanostructures has recently attracted considerable attention. The superposition of a static electric field and an alternating field causes a wealth of new phenomena as a result of photon assisted tunneling [1,2,3]. In all these cases tunneling is accomplished by a static electric field and the radiation influences the barrier penetration probability. An intense radiation field, however, can in fact generate both the tunneling barrier and initiate tunneling. Such a tunneling process has been observed for deep impurities in semiconductors [4]. In contrast to tunneling ionization of atoms, where only electron tunneling takes place [5], phonon–assisted tunneling ionization of impurities in solids is accomplished by two simultaneous tunneling processes, electron tunneling and the redistribution of the vibrational system by defect tunneling.

M., *Mat. Sci. Forum* **38-41**

(1988) p.873; Dabrowski J.
83.
, Jantsch W. and Brunthaller
ıs Tech, 1989) p. 233.

990) p.297; Inst. Phys. Conf.

. R. and Weber E. R., *Phys.*

na K. and Kobayashi S., *Jpn.*

, *J. Appl. Phys.* 83 (1998) p.
roup cited therein.
Langer J. M., Suchocki A.,
ol. *Phys. Lett.* **67** (1995) p.31.
ys. *Lett.* **70** (1997) p.2934.
Jantsch W., *Phys. Rev. Lett.*,

7 (1995) p.2275; Fu C. and
3575.
Appl. Phys. Lett. **71** (1997)

., Mat. Sci. Forum, **258-263**

r J. M., *Physics Lett.* A **222**,

M., Mat. Sci. Forum, **258-263**

Appl. Phys. Lett. **70** (1997)

Technology, 7 (1992) p.364.
rdyna J. K., *Phys. Rev. Lett.*,

ed.
Rev. Lett., **80** (1998) p.2949.
., and Arizmendi L., *Optic*

Vojtowicz T.,Miotkowski I.,

Rev. B **56** (1997) p. 15665.

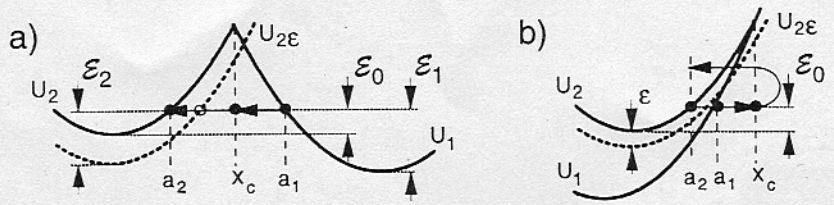


Figure 1: Tunneling trajectories for the ionization of autolocalized (a) and substitutional (b) deep impurities.

2 Theoretical consideration

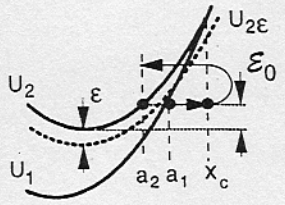
In most cases deep impurities have one bound state which phenomenologically can be approximated by a potential well. The emission and capture of electrons or holes by deep impurities in semiconductors can be considered in the adiabatic approximation. Due to electron–phonon interaction the system consisting of local impurity vibrations and the electron is characterized by two adiabatic potentials $U_1(x)$ and $U_2(x)$ as a function of a configuration coordinate x (see insets in Fig. 3). Following the Huang–Rhys model these adiabatic potentials correspond to the electron bound to the impurity and to the electron detached from the impurity with zero kinetic energy, respectively. The energy separation between the minima of U_1 and U_2 is the thermal ionization energy of the electron ε_T. Thermal emission of carriers from the bound state into the continuum is accomplished by thermal excitation of the system in the adiabatic bound state potential U_1 to a vibrational energy $\mathcal{E}_1$ and tunneling of the impurity configuration from this state into the ionized configuration U_2 with energy $\mathcal{E}_2$ (Fig. 1)[6,7,8,9].

In the presence of an electric field the electron can be emitted at a negative kinetic energy $-\varepsilon$ due to tunneling through the triangular potential barrier formed by the electron potential well and the electric field (see inset in Fig. 4). Hence, the adiabatic potential of the ionized configuration U_2 is shifted to a lower energy $U_{2\varepsilon} \equiv U_2 - \varepsilon$ (Fig. 1,3). Thus electron emission in an electric field is achieved by two tunneling processes, electron tunneling with probability P_e and tunneling of the defect from the adiabatic potential $U_1(\mathrm{x})$ to potential $U_{2\varepsilon}$ with the probability P_d.

The ionization probability may be written as:

$$e(E) = \int\int P_e P_d \exp(-\mathcal{E}_1/k_B T) d\varepsilon d\mathcal{E}_1 \qquad (1)$$

The Boltzmann factor takes into account the thermal excitation of the system in the adiabatic potential U_1.



)calized (a) and substitutional (b)

te which phenomenologically
mission and capture of elec-
ors can be considered in the
ı interaction the system con-
tron is characterized by two
on of a configuration coordi-
–Rhys model these adiabatic
he impurity and to the elec-
ic energy, respectively. The
U_2 is the thermal ionization
arriers from the bound state
citation of the system in the
nal energy $\mathcal{E}_1$ and tunneling
the ionized configuration U_2

ı can be emitted at a negative
triangular potential barrier
tric field (see inset in Fig. 4).
ıfiguration U_2 is shifted to a
on emission in an electric field
unneling with probability P_e
tential $U_1(x)$ to potential $U_{2\varepsilon}$

s:

$_BT)d\varepsilon d\mathcal{E}_1$ (1)

rmal excitation of the system

In the semi–classical approximation, neglecting pre–exponential factors, the defect tunneling probability is given by [7,9]:

$$P_d \propto \exp(-2(S_2 \mp S_1)); \qquad S_i(\mathcal{E}_i) = \frac{\sqrt{2M}}{\hbar} \int_{a_i}^{x_c} dx \sqrt{U_i(x) - \mathcal{E}_i}, \quad i = 1, 2 \quad (2)$$

where M is a mass corresponding to the mode of impurity vibration, a_i and x_c are shown in Fig. 1, and the minus and plus sign are related to the particular impurity configuration shown in Fig. 1a and 1b, respectively.

Electron tunneling in an alternating electric field $E = E_0 \cos(\omega t)$ has been treated theoretically by Keldysh [5] (see also [10]). The tunneling probability is given by:

$$P_e \propto \exp(-2S_e(\varepsilon)); \qquad S_e(\varepsilon) = -\frac{\varepsilon}{\hbar} \int_0^{\tau_e} \frac{1}{\gamma^2} \sinh^2(\omega\tau) d\tau + \frac{\varepsilon\tau_e}{\hbar} \quad (3)$$

Here $\gamma \equiv \sqrt{2m^*\varepsilon}\,\omega/eE$ and $\sinh(\omega\tau_e) = \gamma$; m^* and e are the electron effective mass and charge, respectively, and $\tau_e = \hbar\partial S_e/\partial\varepsilon$ has the meaning of an electron tunneling time [12,13].

The integral Eq. 1 has been calculated using the saddle point method. In the case of weak electric fields, i. e., as long as the saddle point energy $\varepsilon \ll \varepsilon_T$, the exponent in the index can be developed into a power series of ε. Taken into account that $\mathcal{E}_2 = \mathcal{E}_1 - (\varepsilon_T - \varepsilon)$ we obtain

$$S_2 \mp S_1 \simeq (S_2 \mp S_1)|_{\varepsilon=0} - \frac{\varepsilon\tau_2}{\hbar}; \quad \text{with} \quad \tau_2 = \left.\frac{\hbar\partial|S_2|}{\partial\mathcal{E}_2}\right|_{\varepsilon=0} \quad (4)$$

Then the saddle point condition gives

$$\tau_2 = \tau_e; \qquad \tau_2 = \frac{\hbar}{2k_BT} \pm \tau_1 \quad (5)$$

where $\tau_1 = \hbar\partial|S_1|/\partial\mathcal{E}_1|_{\varepsilon=0}$. The first term in Eq. 5 states that the electron tunneling time τ_e is equal to the defect tunneling time τ_2 for tunneling under the potential U_2.

Finally we obtain for the ionization probability:

$$e(E) \propto \exp\left[\frac{E^2}{E_c^{*2}}\right] = \exp\left[\frac{E^2 e^2 (\tau_2^*)^3}{3m^*\hbar}\right] \tag{6}$$

$$(\tau_2^*)^3 = \frac{3}{4\omega^3}(\sinh(2\omega\tau_2) - 2\omega\tau_2) \tag{7}$$

This result shows that $(\tau_2^*)^3$ increases exponentially as a function of $\omega\tau_2$. As the ionization probability itself depends exponentially on the third power of τ_2^* the tunneling ionization is drastically enhanced with rising $\omega\tau_2$. This can be achieved not only by increasing the radiation frequency ω but also by lowering the temperature (Eq. 5). In the limit $\omega\tau_2 \ll 1$ the time constant τ_2^* approaches the tunneling time τ_2 giving the result of the static field regime obtained in [11].

3 Samples and experimental technique

The tunneling ionization of deep impurities by high-intensity FIR radiation with photon energies much smaller than the thermal impurity ionization energy ε_T has been studied for different types of deep impurities: substitutional impurities with weak electron–phonon coupling (Ge:Au, Ge:Hg, Ge:Cu, Ge:Zn, Si:Au, GaP:Te with acceptor concentrations in the range $10^{14} - 10^{15}$ cm^{-3}) and autolocalized DX^- centers with strong electron phonon coupling ($Al_xGa_{1-x}As$:Te, $Al_xGa_{1-x}Sb$:Te with x=0.35 and 0.5). In the investigated temperature range from 4.2 K to 80 K, for autolocalized impurities up to 150 K, practically all impurities are occupied in thermal equilibrium.

The ionization probability has been determined by detecting photoconductivity. The radiation sources used were a pulsed far-infrared molecular laser optically pumped by a TEA-CO_2 laser and the Santa-Barbara Free-Electron-Laser (FEL). Using NH_3, D_2O, CH_3F as active gases for the molecular FIR laser, 40 ns pulses with intensity up to 5 MW/cm^2 have been obtained at 10 frequencies ω in the range from 3.78 THz to 68 THz [14]. The parameters of the FEL are: intensity up to 1 kW/cm^2 and ω = 6.8 THz, 4.5 THz and 3.4 THz [1].

4 Experimental results and analysis

Ionization of deep impurities by far infrared radiation has been observed for all samples in the whole frequency range investigated. Ionization can be attributed to phonon-assisted tunneling over a wide range of temperature, frequency and electric field strength [14].

At not too low temperatures and not too high frequencies the tunneling probability is independent of frequency and exponentially increases with the

ıbility:

$$\left[\frac{E^2e^2(\tau_2^*)^3}{3m^*\hbar}\right] \qquad (6)$$

$$)-2\omega\tau_2) \qquad (7)$$

ntially as a function of $\omega\tau_2$. As ıentially on the third power of τ_2^* ed with rising $\omega\tau_2$. This can be frequency ω but also by lowering the time constant τ_2^* approaches static field regime obtained in [11].

e

by high–intensity FIR radiation thermal impurity ionization en- s of deep impurities: substitu- coupling (Ge:Au, Ge:Hg, Ge:Cu, rations in the range $10^{14}-10^{15}$ strong electron phonon coupling 35 and 0.5). In the investigated olocalized impurities up to 150 K, mal equilibrium.

nined by detecting photoconduc- lsed far–infrared molecular laser ıe Santa–Barbara Free–Electron– tive gases for the molecular FIR V/cm^2 have been obtained at 10)8 THz [14]. The parameters of the 6.8 THz, 4.5 THz and 3.4 THz [1].

adiation has been observed for all ıted. Ionization can be attributed ge of temperature, frequency and

o high frequencies the tunneling exponentially increases with the

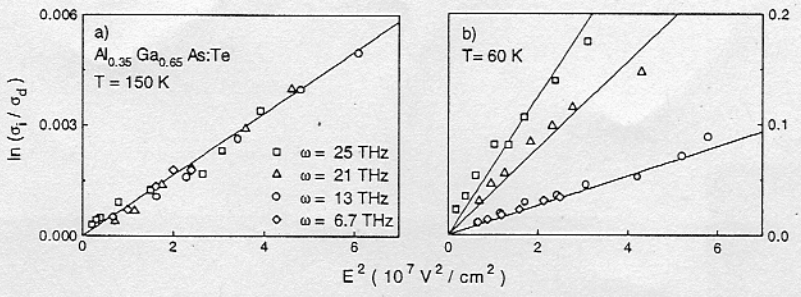


Figure 2: The ionization probability (given by the ratio of the conductivity under illumination and in the dark σ_i/σ_d) of $Al_{0.35}Ga_{0.65}As$:Te as a function of the square of the amplitude of the electric field of the radiation. Lines shows $\propto \exp(E^2/E_c^{*2})$.

square of the electric field strength[a] (see Eq. 6). This is illustrated in Fig. 2a where experimental results obtained with AlGaAs:Te at T = 150 K are shown. In this quasi–static regime the electron tunnels at the momentary magnitude of the electric field in a time shorter than the period of oscillation and thus the electric field acts like a static field. Such a behaviour has been observed for all materials at sufficiently high temperatures. In this case [14,16,17] the characteristic field is given by $E_c^{*2} = (3m^*\hbar)/(\tau_2^{*3}e^2)$ with $\tau_2^* = \tau_2$. In the quasi–static regime tunneling times τ_2 can be determined experimentally. The results are shown in Fig. 3.

This frequency independent tunneling is limited to frequencies ω with $\omega\tau_2 < 1$ (Eq. 7) The enhancement of tunneling at frequencies higher than the reciprocal tunneling time has been anticipated in a number of theoretical works [5,10,18,19,20], but has been demonstrated experimentally only recentely [21]. In contrast to static electric fields where the electron tunnels at a fixed energy, in alternating fields the energy of the electron is not conserved during tunneling (see inset in Fig. 4). In this case the electron can absorb energy from the field, which leads to a sharp increase of the tunneling probability with increasing frequency. This effect has been observed for various impurities in different semiconductors and is demonstrated for AlGaAs:Te in Fig. 2b. The ionization probability still depends exponentially on the square of the electric field strength but the ionization becomes frequency dependent and is drastically enhanced with rising frequency.

[a] In the case of charged impurities (all substitutional impurities investigated) a deviation from the field dependence $e(E) \propto \exp(E^2/E_c^{*2})$ can be seen in relatively low field strength (up to 1 kV/cm) where the defects are thermally ionized through the Poole–Frenkel effect and the ionization probability is proportional to $e(E) \propto \exp(\sqrt{(Ze^3E/\kappa)}/k_BT)$ [14,15,16].

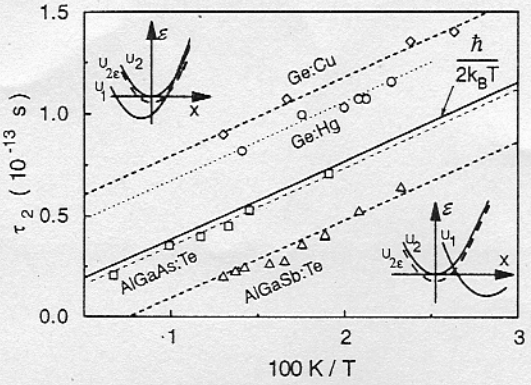
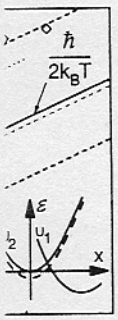


Figure 3: Tunneling times τ_2 as a function of $1/T$ for different samples. The full line shows $\hbar/2k_BT$, the broken lines are plotted according to Eq. 5. Insets: Adiabatic potentials for substitutional impurities (top left) and autolocalized impurities (bottom right).

In Fig. 4 the ratio τ_2^*/τ_2 calculated after Eq. 7 is plotted as a function of $\omega\tau_2$ and compared to experimental results obtained from measured values of E_c^* for various frequencies, temperatures and materials. The tunneling times τ_2 were determined from frequency independent values of E_c^*. The experimental results shown in Fig. 4 are grouped according to the materials. For each material the variation of the value of $\omega\tau_2$ has been obtained by applying different radiation frequencies in the range from 6.7 THz to 54 THz and different temperatures between 4.2 K and 150 K. It should be pointed out that the theory leading to good agreement with experiment does not contain any fitting parameters.

The emission probability as a function of the electric field given by Eq. 6 was obtained in the limit that corrections to thermal emission resulting from electron tunneling are small, i.e., the energy of electron tunneling ε is much smaller than the defect tunneling energy $\mathcal{E}_0$ and the energy of thermal ionization ε_T. In the opposite limit, $\varepsilon > \varepsilon_T, \mathcal{E}_0$, direct carrier tunneling from the ground state into continuum, without participation of phonons, becomes dominant. Direct electron tunneling occurs at the crossing of the $U_{2\varepsilon}$ and U_1 potential curves, where an electronic transition is possible without any change in the configuration coordinate. This effect leading to weaker field dependence as compared to phonon–assisted ionization, determines the ionization process at very high fields [14,16,22].

The phonon–assisted ionization of deep impurities in semiconductors by contactless application of short pulses of terahertz radiation has been proposed as a new method for the characterization of defects [14,17,23,24]. The field de-



3

nt samples. The full line shows
nsets: Adiabatic potentials for
ies (bottom right).

plotted as a function of $\omega\tau_2$
measured values of E_c^* for
he tunneling times τ_2 were
. The experimental results
ials. For each material the
pplying different radiation
nd different temperatures
that the theory leading to
ny fitting parameters.

lectric field given by Eq. 6
al emission resulting from
ctron tunneling ε is much
he energy of thermal ion-
ect carrier tunneling from
ation of phonons, becomes
crossing of the $U_{2\varepsilon}$ and U_1
ossible without any change
to weaker field dependence
ines the ionization process

ities in semiconductors by
adiation has been proposed
ts [14,17,23,24]. The field de-

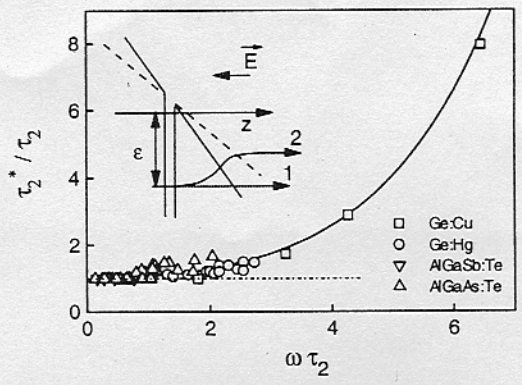


Figure 4: Ratio τ_2^*/τ_2 as a function of $\omega\tau_2$. The line shows the dependence according to Eq. 7 Inset: Electron tunneling trajectory: (1) in a static electric field, and (2) in an alternating field.

pendence of the signal allows one to determine the defect tunneling times, the Huang–Rhys parameter and the basic structure of the adiabatic defect potentials. The Poole–Frenkel effect, which can be observed for charged impurities only, can be used to determine the defect charge state.

Finally, our measurements have been carried out with deep impurities in semiconductors, however, because tunneling is crucial in numerous processes in physics, chemistry, and biology we expect that an enhancement of tunneling by contactless application of coherent radiation will have significant consequences.

Acknowledgments

Financial support by the DFG and the RFFI are gratefully acknowledged. I.W. and E.H. would like to thank O.D. Dubon for active help and discussion.

References

1. P.S.S. Guimaraes, B.J. Keay, J.P. Kaminski, S.J. Allen, Jr., P.F. Hopkins, A.C. Gossard, L.T. Florez, and J.P. Harbinson, Phys. Rev. Lett. **70**, 3792 (1993).
2. B. J. Keay, S.J. Allen, Jr., J. Gallan, J. P. Kaminski, K.L. Campman, A. C. Gossard, U. Bhattacharya, and J.W. Rodwell, Phys. Rev. Lett. **75**, 4098 (1995).
3. C.J.G.M Langerak, B.N. Murdin, B.E. Cole, J.M. Chamberlain, M. Henini, M. Pate, and G. Hill, Appl. Phys. Lett. **67**, 3453 (1995).

4. S.D. Ganichev, W. Prettl, and P.G. Huggard, Phys. Rev. Lett. **71**, 3882 (1993).
5. L.V. Keldysh, Sov. Phys. JETP **20**, 1307 (1965).
6. S. Makram–Ebeid, and M. Lannoo, Phys. Rev. B **25**, 6406 (1982).
7. T. Markvart, J. Phys. C **17**, 6303 (1984).
8. P. T. Landsberg, *Recombination in Semiconductors* (Cambridge University Press, New York, 1991).
9. V.N. Abakumov, V.I. Perel, and I.N. Yassievich, *Nonradiative Recombination in Semiconductors*, edited by V.M. Agranovich and A.A. Maradudin, Modern Problems in Condensed Matter Sciences Vol. 33 (North Holland, Amsterdam, 1991).
10. L.D. Landau, and E.M. Livshitz, *Quantum Mechanics* (Pergamon, Oxford, 1977), p. 287.
11. V. Karpus, and V. I. Perel, Sov. Phys. JETP **64**, 1376 (1986).
12. M. Büttiker, and R. Landauer, Phys. Rev. Lett. **49**, 1739 (1982).
13. R. Landauer, and Th. Martin, Rev. of Mod. Phys. **66**, 217 (1994).
14. S.D. Ganichev, W. Prettl, and I.N. Yassievich, review in Phys. Solid State **39**, 1703 (1997).
15. S.D. Ganichev, J. Diener, I.N. Yassievich, and W. Prettl, Europhys. Lett. **29**, 315 (1995).
16. S.D. Ganichev, I.N. Yassievich, and W. Prettl, Semicond. Sci. and Techn. **11**, 679 (1996).
17. S.D. Ganichev, J. Diener, I.N. Yassievich, W. Prettl, B.K. Meyer, and K.W. Benz, Phys. Rev. Lett. **75**, 1590 (1995).
18. Yu. A. Bychkov, and A. M. Dykhne, Sov. Phys. JETP **31**, 928 (1970).
19. B.I. Ivlev, and V.I. Mel'nikov, Phys. Rev. Lett. **55**, 1614 (1985).
20. M.V. Ammosov, N.B. Delone, V.P. Krainov, Sov. Phys. JETP **64**, 1191 (1986).
21. S.D. Ganichev, E. Ziemann, Th. Gleim, W. Prettl, I.N. Yassievich, V.I. Perel, I. Wilke, and E.E. Haller, Phys. Rev. Lett. **80**, 2409 (1998).
22. S.D. Ganichev, J. Diener, and W. Prettl, Solid State Comm. **92**, 883 (1994).
23. E. Ziemann, S.D. Ganichev, I.N. Yassievich, K. Schmalz, and W. Prettl, to be published, MRS Symp. Proc., San Francisco (1998).
24. S.D. Ganichev, W. Raab, E. Zepezauer, W. Prettl, and I. Yassievich, Phys. Rev. B **55**, 9243 (1997).

24th International Conference on

THE PHYSICS OF SEMICONDUCTORS

Jerusalem, Israel

August 2 – 7, 1998

Editor

DAVID GERSHONI
Department of Physics and Solid State Institute
Technion – Israel Institute of Technology

World Scientific
Singapore • New Jersey • London • Hong Kong

Published by

World Scientific Publishing Co. Pte. Ltd.

P O Box 128, Farrer Road, Singapore 912805

USA office: Suite 1B, 1060 Main Street, River Edge, NJ 07661

UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Proceedings of the 24th International Conference on
THE PHYSICS OF SEMICONDUCTORS

ISBN 981-02-3613-1

Printed in Singapore by Uto-Print