Intense Terahertz Excitation of Semiconductors

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PREFACE

The rapidly growing field of terahertz physics and technology can roughly be divided into two areas. The first is manly concerned with the development and application of continuous working (*cw*) coherent semiconductor sources and molecular gas lasers as well as of ultrafast time-domain spectroscopy based on femtosecond radiation pulses which might replace, in the near future, classical Fourier transform far-infrared spectroscopy. The applications of current interest in this area, as far as they go beyond linear spectroscopy and ultrafast dynamics of solids, include plasma diagnostics, high-speed communication, environmental monitoring, and various imaging methods like biomedical imaging, quality control, and terahertz tomography. Another important technique making use of coherent terahertz sources comprises terahertz heterodyne receivers for astronomical purposes.

The second area, emerging only lately, deals with radiation–matter interaction in the terahertz spectral range at very high power levels as they are available today from optically pumped molecular lasers, free-electron lasers, and by nonlinear optical processes from intense femtosecond lasers in the near-infrared. Most of the experimental work has been devoted to intense excitation of semiconductors exploring a great variety of new basic physics and yielding data on the dynamics of carriers valuable for applications and the development of devices. This book focuses exclusively on this topic providing the first comprehensive treatment of high-power terahertz laser applications to semiconductor and semiconductor structures. Written on a post-graduate level it attempts to fill the gap between nonlinear optical phenomena in the visible and near-infrared range and nonequilibrium microwave transport. It focuses on a core topic of semiconductor physics offering a description of the state of the art of the field and providing background information with exhaustive references to the current literature. The reader is introduced to physical phenomena characteristic of the terahertz range which occur at the transition from semiclassical physics with a classical field amplitude and the fully quantized limit with photons.

The book covers tunneling processes in high-frequency fields, nonlinear absorption of radiation, nonlinear optics in the classical sense, hot electron dynamics, Bloch oscillations, ponderomotive action of the radiation field on a free electron gas, photoelectric and optoelectronic effects, and terahertz spin dependent phenomena. In addition, the reader is introduced to the basics of the generation of high-power coherent radiation in the terahertz range, experimental methods, terahertz optical components, and various schemes of intensive short terahertz pulse detection.

The book deals with semiconductor physics but the physical mechanisms like tunneling in alternating electromagnetic fields and experimental methods as, for instance, contactless application of high electric fields are also important in other fields and may be utilized in areas like condensed matter physics, chemistry, biophysics, medicine, etc. The prerequisites for this book are knowledge of basic quantum mechanics and electromagnetism and some familiarity with semiconductor physics and materials sciences. It will be useful not only to scientists but also to advanced undergraduate students who are interested in terahertz electronics, nonlinear optical and photoelectric phenomena, free carrier dynamics, and instrumentation for high-power terahertz research.

The book extends for the first time in the form of a monograph previous books on infrared physics which dealt with linear optical processes and low-power instrumentation. Our intention was to concentrate on physical essentials on the interaction of terahertz radiation with semiconductors, therefore we did not penetrate deeply into the theory, rather we presented for all processes easily conceivable model-like illustrations and discussed a wide range of experimental work in detail.

During the work this book is based on and in writing the book we have received help and information from a large number of colleagues and friends all over the world. We thank them all but it would be impossible to name them and to present their scientific contributions to our work. All that we can do here is to mention only those who helped us preparing this book in all aspects including many exciting conversations and, last but not least, technical support. We thank Vasily Bel'kov, Eugene Beregulin, Sergey Danilov, Olga Ganicheva, Stephan Giglberger, Leonid Golub, Christoph Hoffmann, Eougenious Ivchenko, Igor Kotel'nikov, Matei Olteanu, Barbara Prettl, Karl Renk, Kirill Alekseev, Petra Schneider, Alexander Shul'man, and Wolfgang Weber.

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INTRODUCTION

This monograph summarizes recent investigations of nonequilibrium processes in semiconductors caused by high-power coherent radiation at terahertz frequencies. The terahertz frequency range may loosely be defined by the limiting frequencies 0.2 THz and 15 THz corresponding to wavelengths extending from 1500 μm to 20 μm. The development of the terahertz range took place from both sides of its spectral extensions, from the lower frequency infrared side and the higher frequency millimeter wave side. Depending on the approach to terahertz frequencies, the expressions far-infrared (FIR) and submillimeter waves were coined for this part of the electromagnetic spectrum while the term terahertz came only recently into custom. We will use here the terms terahertz, far-infrared, and submillimeter synonymously. Though this spectral regime was fully explored in the last few decades only, infrared physics is in fact not a new area of science. The infrared was discovered by Sir William Herschel in 1800 by his famous experiment using thermometers with blackened bulbs as radiation detectors. It took exactly a hundred years until Max Planck derived in 1900 his famous formula describing the spectrum of thermal black-body sources and herewith laying the foundation stone of quantum mechanics. Thermal sources are still in use in far-infrared spectrometers.

In the 20th century infrared physics rapidly advanced to longer wavelengths. Today the terahertz range is a well developed part of the electromagnetic spectrum with a large variety of coherent sources up to power levels in the kilowatt and megawatt ranges, like molecular lasers, frequency tunable free-electron lasers, and femtosecond-fast broadband sources. Furthermore, devices like filters and windows, as well as a wide range of detector systems suitable for different tasks are readily available. The frequently addressed so-called terahertz-gap refers, indeed, only to the still present lack of small coherent terahertz sources, like semiconductor lasers or Bloch oscillators, useful for short range communication.

Spectroscopy at terahertz frequencies is of great importance for condensed matter physics and in particular for semiconductors and semiconductor structures because the characteristic energies of many elementary excitations lie in this spectral range. Among them are plasma oscillations, ionization energies of typical shallow donors and acceptors, cyclotron resonance and spin-flip energies, the characteristic size-quantization energies of low-dimensional electron systems, and optical phonon energies. Furthermore the relaxation rates of free and bound excited carriers and scattering rates of free carriers coincide with the terahertz regime. The photon energies in this part of the electromagnetic spectrum range from about 1 to 35 meV being much smaller than the energy gap of usual semi-

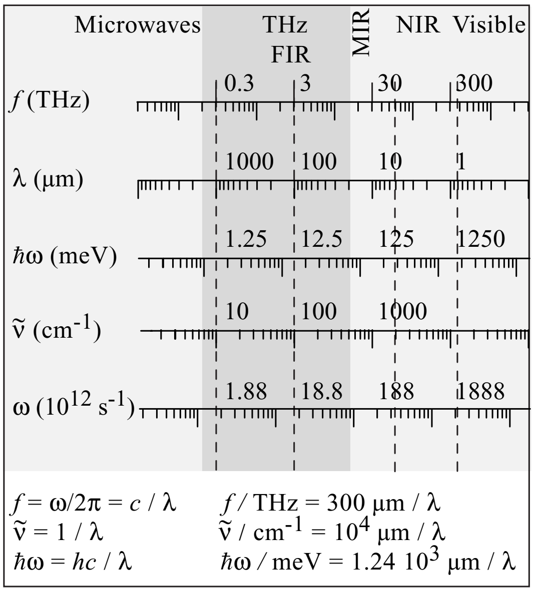

FIG. 1. Relation between various characteristics of the THz spectrum.

conductors. In Fig. 1 the slot of the electromagnetic spectrum dealt with here is plotted.

Conventional linear spectroscopy in this spectral regime uses incoherent broadband thermal sources applying Fourier transform spectroscopy. Though this spectroscopic technique makes use of the available radiation intensity in a very economical way, the low brightness of thermal sources limits its sensitivity and resolution. At lower frequencies, say below 0.5 THz, coherent sources like backward wave oscillators, Gunn oscillators and IMPATT diodes have been utilized, emitting narrow lines at moderate power with narrow tuning ranges.

Radically new fields in the investigation of semiconductors became accessible by the development of high-power pulsed terahertz lasers like molecular lasers pumped by TEA (Transversely Excited Atmospheric pressure) CO_2 lasers and, subsequently, of frequency tunable FEL (free-electron lasers). Both types of terahertz lasers are capable of delivering short pulses of high intensity up to a few megawatts. Furthermore the limitations of broadband Fourier transform spectroscopy are lifted by the rapidly evolving field of time-domain spectroscopy which relies on intense near-infrared femtosecond laser pulses.

In the terahertz range high-radiation intensity gives rise to a variety of nonlinear phenomena whose characteristic features are basically different from the corresponding effects at microwave frequencies as well as in the range of visible radiation. This is due to the fact that in the electron–radiation interaction the transition from semiclassical physics with a classical field amplitude to the fully quantized limit with photons occurs at terahertz frequencies. The possibility to vary both the frequency and the intensity of high-power radiation sources in a wide range yields the unique opportunity to study the same physical phenomenon in both limits. By properly varying the frequency or intensity of radiation one can achieve that either the discrete properties of light quanta or the wave character of the radiation field dominates the radiation–matter interaction.

Since the photon energies of terahertz radiation are much smaller than the energy gap of typical semiconductors, there can be no direct one-photon generation of free carriers. Hence the observation of relatively weak effects of carrier redistribution in momentum space and on the energy scale becomes possible. These studies are supported by another attractive feature of terahertz spectroscopy that stems from the number of photons in the radiation field. At a given intensity the photon flux is much larger than in the visible range. Hence photon number dependent experiments like radiation-induced electric currents can be observed with higher sensitivity.

The book is organized in the following way. In the first chapter the terahertz related experimental technique is covered including high-power laser sources, detectors of intense radiation, and optical components like windows and filters as well as experimental methods suitable for terahertz investigations. The second chapter deals with tunneling phenomena in high-frequency alternating fields comprising solely terahertz field induced tunneling and terahertz radiation mediated tunneling in static electric fields. Chapter 3 describes multiphoton transitions in the perturbative limit and beyond, resulting in fully developed nonlinearity where quantum interference effects control the absorption of photons. In Chapter 4 terahertz radiation induced saturation of absorption is presented including incoherent as well as coherent saturation effects. Chapters 5 is devoted to heating of free carriers by terahertz radiation focusing on nonlinear phenomena. Among them light impact ionization shows that at intense terahertz irradiation electron–hole pairs can be generated in semiconductors though the photon energies are several tens of times less than the energy gap. Chapter 6 gives an overview on nonlinear optics addressing harmonic generation, side-band mixing, and the dynamic Franz–Keldysh effect approaching the nonperturbative limit. Photoelectric phenomena are the subject of Chapter 7 describing a large number of mechanisms causing photocurrents like the photon drag effect, the linear and the circular photogalvanic effect, the spin-galvanic effect, the magneto-gyrotropic effect and other magnetic field induced photocurrents as well as terahertz radiation induced monopolar spin orientation. The last chapter gives the state of the art of Bloch oscillations in semiconductor superlattices exposed to intense terahertz radiation. Finally in the appendix the spin splitting in the band structure of two-dimensional semiconductor systems is presented which is important for terahertz radiation driven spin-photocurrents.