QUANTUM ENGINEERING

Quantum engineering – the design and fabrication of quantum coherent structures – has emerged as a field in physics with important potential applications. This book provides a self-contained presentation of the theoretical methods and experimental results in quantum engineering.

The book covers such topics as the quantum theory of electric circuits; theoretical methods of quantum optics in application to solid-state circuits; the quantum theory of noise, decoherence and measurements; Landauer formalism for quantum transport; the physics of weak superconductivity; and the physics of a 2-dimensional electron gas in semiconductor heterostructures. The theory is complemented by up-to-date experimental data to help put it into context. Aimed at graduate students in physics, the book will enable readers to start their own research and apply the theoretical methods and results to their current experimental situation.

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Theory and Design of Quantum Coherent Structures

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To my family

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Preface

It is always risky to combine well-known and well-tested notions in order to describe something new, since the future usage of such combinations is unpredictable. After "quantum leaps" were appropriated by the public at large, nobody, except physicists and some chemists, seems to realize that they are exceedingly small, and that breathless descriptions of quantum leaps in policy, economy, engineering and human progress in general may actually provide an accurate, if sarcastic, picture of the reality. When the notion of the "marketplace of ideas" was embraced by academia, scientists failed to recognize that among other things this means spending 95% of your resources on marketing instead of research.[1] Nevertheless, "quantum engineering" seems a justified and necessary name for the fast-expanding field, which, in spite of their close relations and common origins, is quite distinct from both "nanotechnology" and "quantum computing" in scope, approaches and purposes. Its subject covers the theory, design, fabrication and applications of solid-state-based structures, which can maintain quantum coherence in a controlled way. In a nutshell, it is about how to build devices out of solid-state qubits, and how they can be used.

The miniaturization of electronic devices to the point where quantum effects must be taken into account produced much of the momentum behind nanotechnology, together with the need to better understand and control matter on the molecular level coming from, e.g., molecular biology and biochemistry (see, e.g., Mansoori, 2005, Chapter 1). One also often uses the term "mesoscopic physics", especially with respect to solid-state devices, meaning objects on an intermediate scale between truly microscopic (single atoms or small molecules) and truly macroscopic. Despite their comparatively large size ($\sim 10^{11} - 10^{12}$ particles), mesoscopic systems maintain enough quantum coherence so that quantum effects really matter (e.g., Imry, 2002, Chapter 1). The experimental techniques and theoretical

[1] See, e.g., Chaize (2001); Menand (2010).

understanding developed in these fields strongly contributed to the development of quantum engineering.

Another, very strong push was delivered by quantum computing. After the original papers (Feynman, 1985, 1996; Deutsch, 1985) indicated the direction, i.e., the *essential* use of quantum properties of a system for computation, and the discoveries of Shor's (Ekert and Josza, 1996; Shor, 1997) and Grover's (Grover, 1997, 2001) algorithms brought the promise of a qualitative change in computing capabilities, the field immediately became the focus of an enormous amount of attention and funding, which produced some spectacular results at the proof-of-principle level (and in the related field of quantum communications, including quantum key distribution, commercial devices are currently available).

The physical side of the research on quantum computing is guided by DiVincenzo's criteria (DiVincenzo and Loss, 1998; DiVincenzo, 2000):

(i) A scalable physical system with well-characterized qubits.
(ii) The ability to initialize the state of the qubits to a simple fiducial state, such as $|000...\rangle$.
(iii) Long relevant decoherence times, much longer than the gate operation time.[2]
(iv) A universal set of quantum gates.
(v) A qubit-specific measurement capability.

Scalability is first for a reason: it is the hardest property to achieve in conjunction with the requirement for a long enough global decoherence time. Solid-state-based devices were natural candidates from this point of view, despite the uncomfortably high number of degrees of freedom in both the qubits and the surroundings, which threatened to make quantum decoherence times in the system uselessly short. Moreover, this large number of degrees of freedom made such devices suspect, since their operation as qubits would require the regular production of "Schrödinger's cat"-superpositions of macroscopic quantum states, an admittedly hard task for even a single experiment (Leggett, 1980). Superconducting devices and quantum dots gave some of the best promise of scalability while holding the disruption of quantum coherence to an acceptable minimum and satisfying the rest of DiVincenzo's criteria. Research results (e.g., Nakamura et al., 1999; Friedman et al., 2000; van der Wal et al., 2000; Martinis et al., 2002; Vion et al., 2002; Hayashi et al., 2003; Elzerman et al., 2004; Hanson et al., 2005) justified the expectations that quantum coherence can be preserved in these structures after all, and made the kind of experiments only hoped for by Leggett (1980) almost routine.

[2] The decoherence time is some characteristic time after which the system loses its specific quantum correlation; see Section 1.2.2.

Meanwhile Leggett (2002a) stressed the need to test the limits of quantum mechanics through realizing truly macroscopic "Schrödinger's cat" states. He found special reasons for optimism with the successful development in the field of superconducting qubits (Leggett, 2002b). The operation of such devices on a large enough scale would either confirm or refute the applicability of quantum mechanics to arbitrarily large systems, with fundamental consequences for science. Therefore, putting more and more qubits together while maintaining their quantum coherence is a worthwhile task. Whether a working code-cracking or database-searching quantum computer is actually built in the process would be, of course, a minor corollary to such a momentous development.

In this book I concentrate on two directions in quantum engineering, using as building blocks superconducting qubits and qubits based on a two-dimensional electron gas (2DEG). The reason is partly subjective – this is where my expertise is – and partly objective – these two kinds of devices are well understood from the theoretical point of view and are being successfully fabricated and investigated by the experimentalists, using the rich toolset of solid-state physics. This allows me to illustrate the theoretical methods with actual experimental data, more often than not being in quantitative agreement with theoretical predictions (which is a must for any kind of "engineering"). Being a theorist, I can only discuss the theoretical part of the toolset, which helped keep the volume of this book reasonable. Quantum engineering takes its theoretical tools from many, rather distant, chapters of theoretical physics, and I restricted the content to the most useful and widely used techniques. The goal was to provide the reader with enough technical information to be able to deal with current research papers and to start out on their own work in this field.

The book can be used as the basis for one-term graduate courses, with the only prerequisite being the knowledge of basic quantum mechanics and solid-state physics. The topics can be, for example, "Superconducting qubits" (Chapters 1, 2, 4 and 5); "2DEG quantum devices" (Chapters 1, 3 and 5); "Mesoscopic quantum transport" (Chapters 1 to 4), and, of course, "Quantum engineering". The sections and paragraphs which contain additional material, not essential for understanding the rest, are marked with asterisks. The bibliography is, of course, not exhaustive, due to the fast development and already very large volume of research, but I did my best to include all the key research papers and reviews.

Knocking on wood, I was always lucky with teachers, colleagues and friends. Most of what is contained in this book I learned from them or with them; it will be my own fault if I do not convey this knowledge properly. I am greatly indebted to I. Affleck, M. Amin, S. Ashhab, O. Astafiev, D. Averin, A. Balanov, V. Barzykin, A. Blais, M. Everitt, A. Golubov, M. Grajcar, E. Il'ichev, M. Jonson, I. Kulik, F. Kusmartsev, A. Maassen van den Brink, K. Maruyama, H.-G. Meyer, F. Nori,

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