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The birth of the semiconductor superlattice*

L. Esaki

IN 1969, research on artificially structured materials was initiated with a proposal for an engineered semiconductor superlattice with a one-dimensional periodic potential by Esaki and Tsu[1,2]. In anticipation of advancement in controlled epitaxy of ultrathin layers, two types of superlattices were envisioned: doping and compositional, as shown at the top and bottom of Figure 1, respectively.

Before arriving at the superlattice concept, we were examining the feasibility of structural formation of potential barriers and wells that were thin enough to exhibit resonant tunneling[3]. A resonant tunnel diode[4,5] appeared to have more spectacular characteristics than the Esaki tunnel diode[6], the first quantum electron device consisting of only a single tunnel barrier. It was thought that advanced technologies with semiconductors might be ready for demonstration of de Broglie electron waves. Resonant tunnelling can be compared to the transmission of an electromagnetic wave through a Fabry–Perot resonator. The equivalent of a Fabry–Perot resonant cavity is formed by the semiconductor potential well sandwiched between the two potential barriers.

The idea of the superlattice occurred to us as a natural extension of double-, triple- and multiple-barrier structures: the superlattice consists of a series of potential wells coupled by resonant tunnelling. An important parameter for the observation of quantum effects in the structure is the phase-coherent, length which approximates to the electron mean free path. This depends on bulk as well as the interface quality of crystals, and also on the temperatures and values of the effective mass. As schematically illustrated in Figure 2, if characteristic dimensions such as superlattice periods or well widths are reduced to less than the phase-coherent length, the entire electron system will enter a mesoscopic quantum regime of low dimensionality, being in a scale between the macroscopic and the microscopic. Our proposal was indeed to explore quantum effects in the mesoscopic regime.

The introduction of the one-dimensional superlattice potential perturbs the band structure of the host materials, yielding a series of narrow subbands and forbidden gaps which arise from the subdivision of the Brillouin

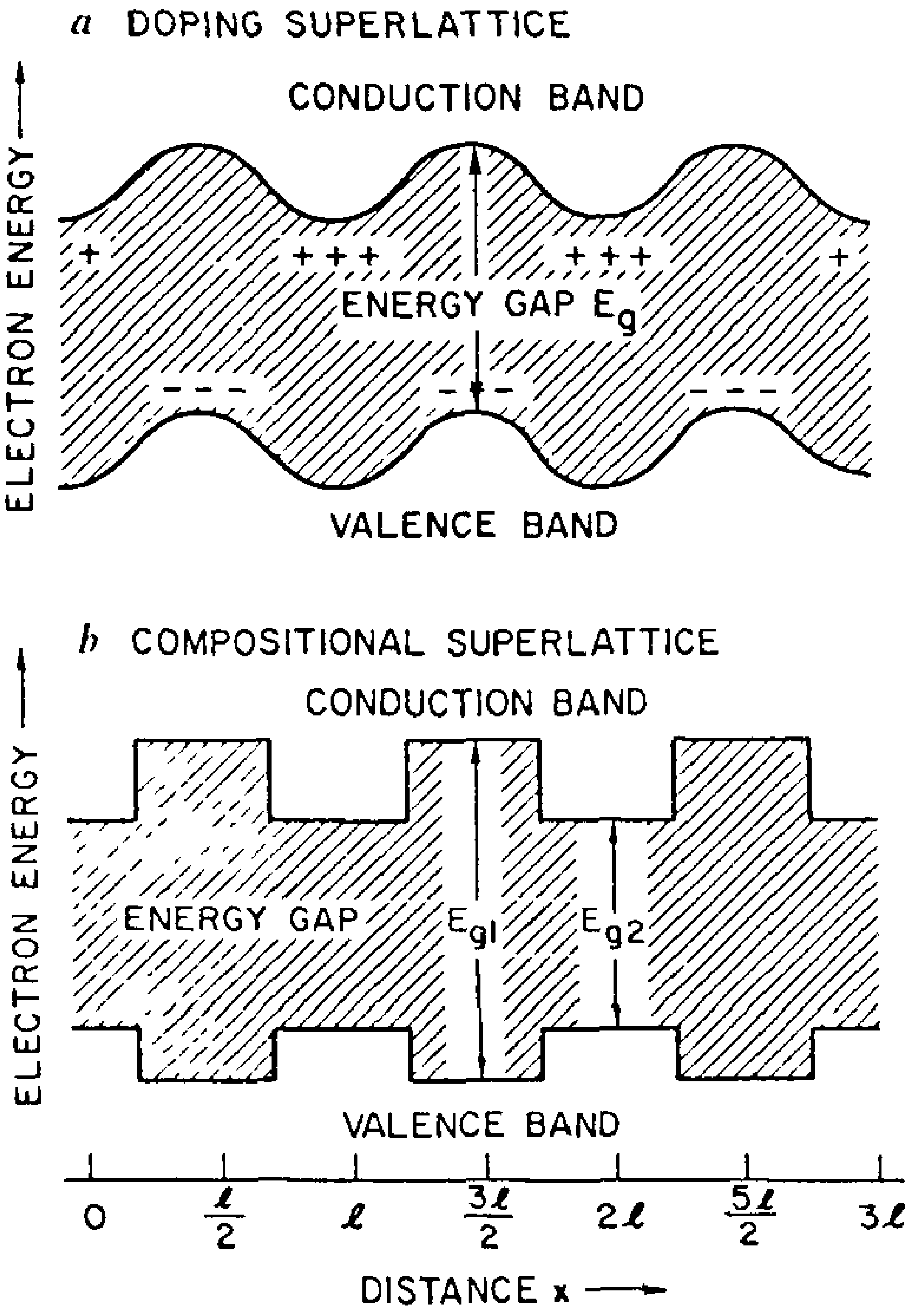

Figure 1. Spatial variation of the conduction and valence band edges in two types of superlattices: *a* doping, *b* compositional

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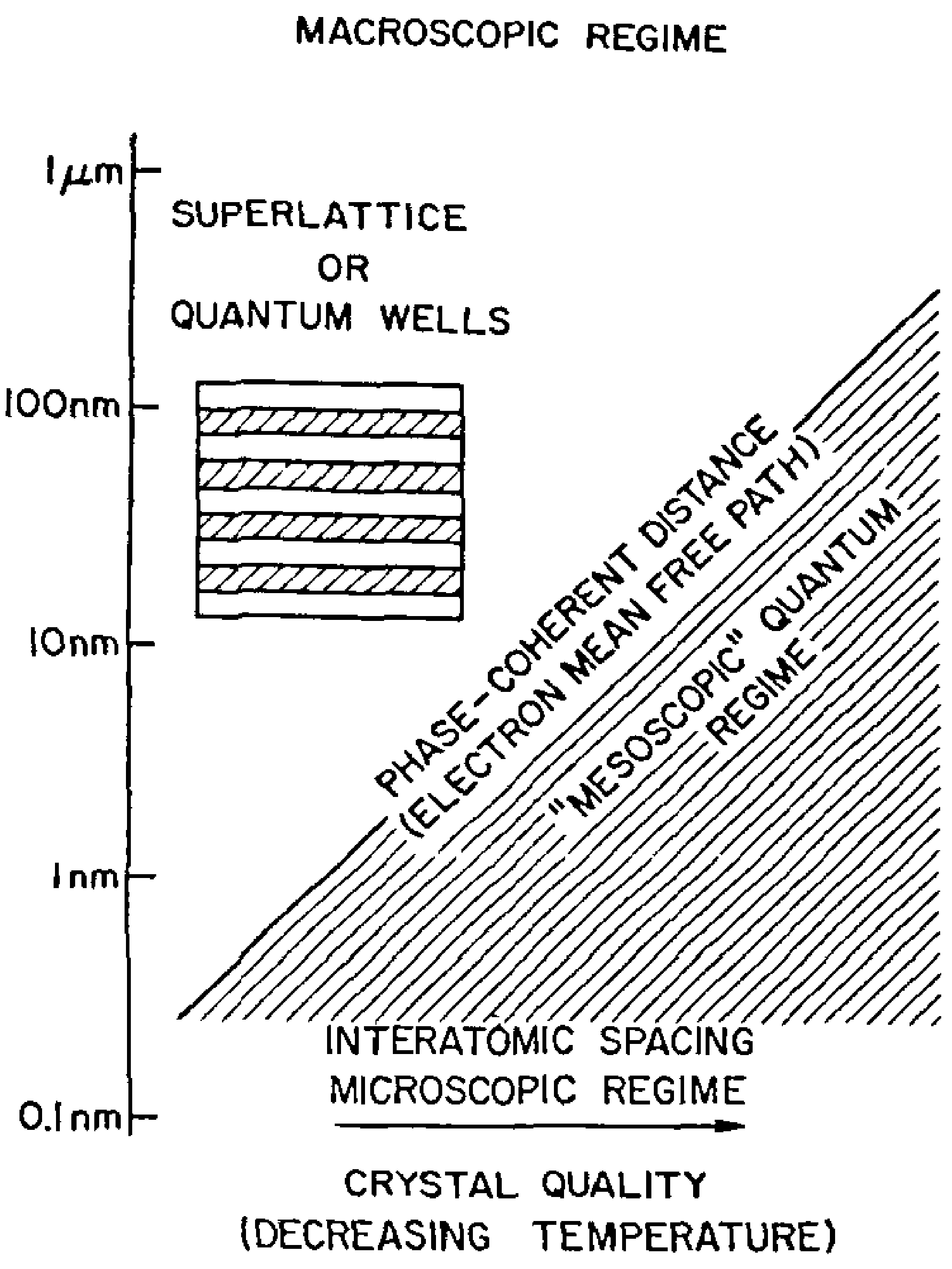

Figure 2. Schematic illustration of a 'mesoscopic' quantum regime (hatched) with a superlattice or quantum wells in the inset

zone into a series of minizones. Thus, the superlattice was expected to exhibit unprecedented electronic properties. At the inception of the superlattice idea, it was recognized that the long, tailored lattice period provided a unique opportunity to exploit electric-field-induced effects. The electron dynamics in the superlattice direction was analysed for conduction electrons in a narrow subband of a highly perturbed energy–wave-vector relationship. The result led to the prediction of the occurrence of a negative differential resistance at a modestly high electric field, which could be a precursor of the Bloch oscillation. The superlattice, apparently, allows us to enter the regime of electric-field-induced quantization: the formation of Stark ladders,[7,8] for example, can be proved in a (one-dimensional) superlattice,[9] whereas in natural (three-dimensional) crystals the existence and real nature of these localized states in a high electric field have been controversial[10,11].

This was, perhaps, the first proposal which advocated to the engineer with advanced thin-film growth techniques a new semiconductor material designed by applying the principles of the quantum theory. The proposal was indeed made to the US Army Research Office (ARO), a funding agency, in 1969, having daringly stated, with little confidence in a successful outcome at the time, 'the study of superlattices and observations of quantum-mechanical effects on a new physical scale may provide a valuable area of investigation in the field of semiconductors'.

Although this proposal was favourably received by ARO, the original version of the paper[1] was rejected for publication by *Physical Review* on the referee's unimaginative assertion that it was *too speculative* and involved *no new physics*. The shortened version published in *IBM J. Res. Develop.*[2] was selected as a Citation Classic by the Institute for Scientific Information (ISI) in July 1987. Our 1969 proposal was cited as one of the most innovative ideas at the ARO 40th Anniversary Symposium, Durham, North Carolina, 1991.

At any rate, with the proposal, we initiated such a formidable task as to make a *gedanken* experiment a reality. In some circles, the proposal was criticized as close to impossible. One of the objections was that a manmade structure with compositional variations in the order of several nanometers could not be thermodynamically stable because of interdiffusion effects. Fortunately, however, it turned out that interdiffusion was negligible at the temperatures involved.

In 1970, Esaki *et al.*[12] studied a GaAs–$GaAs_{0.5}P_{0.5}$ superlattice with a period of 20 nm synthesized with CVD (chemical vapour deposition) by Blakeslee and Aliotta[13]. Although transport measurements failed to reveal any predicted effect, the specimen probably constituted the first strained-layer superlattice having a relatively large lattice mismatch. Early efforts in our group to obtain epitaxial growth of $Ge_{1-x}Si_x$ and $Cd_{1-x}Hg_xTe$ superlattices were soon abandoned because of the rather serious technological problems at that time. Instead, we focused our research effort on compositional GaAs–$Ga_{1-x}Al_xAs$ superlattices grown with MBE (molecular beam epitaxy). In 1972, Esaki *et al.*[14] found a negative resistance in such superlattices, which was, for the first time, interpreted in terms of the superlattice effect.

Following the derivation of the voltage dependence of resonant tunnel current[5], Chang *et al.*[15] observed the current–voltage characteristics with a negative resistance. Subsequently, Esaki and Chang[16] measured quantum transport properties in a superlattice with a narrow bandwidth, which exhibited an oscillatory behaviour. Tsu *et al.*[17] performed photocurrent measurements on superlattices subject to an electric field perpendicular to the plane layers with the use of a semitransparent Schottky contact, which revealed their miniband configurations.

Heteroepitaxy is of great interest for the growth of compositional superlattices. Innovations and improvements in epitaxial techniques such as MBE and MOCVD (metalloorganic chemical vapour deposition) have made it possible to prepare high-quality heterostructures. Such structures possess predesigned potential profiles and impurity distributions with dimensional control close to interatomic spacing. This great precision has cleared access to the mesoscopic quantum regime[18,19].

Since a one-dimensional potential can be introduced along with the growth direction, famous examples in the

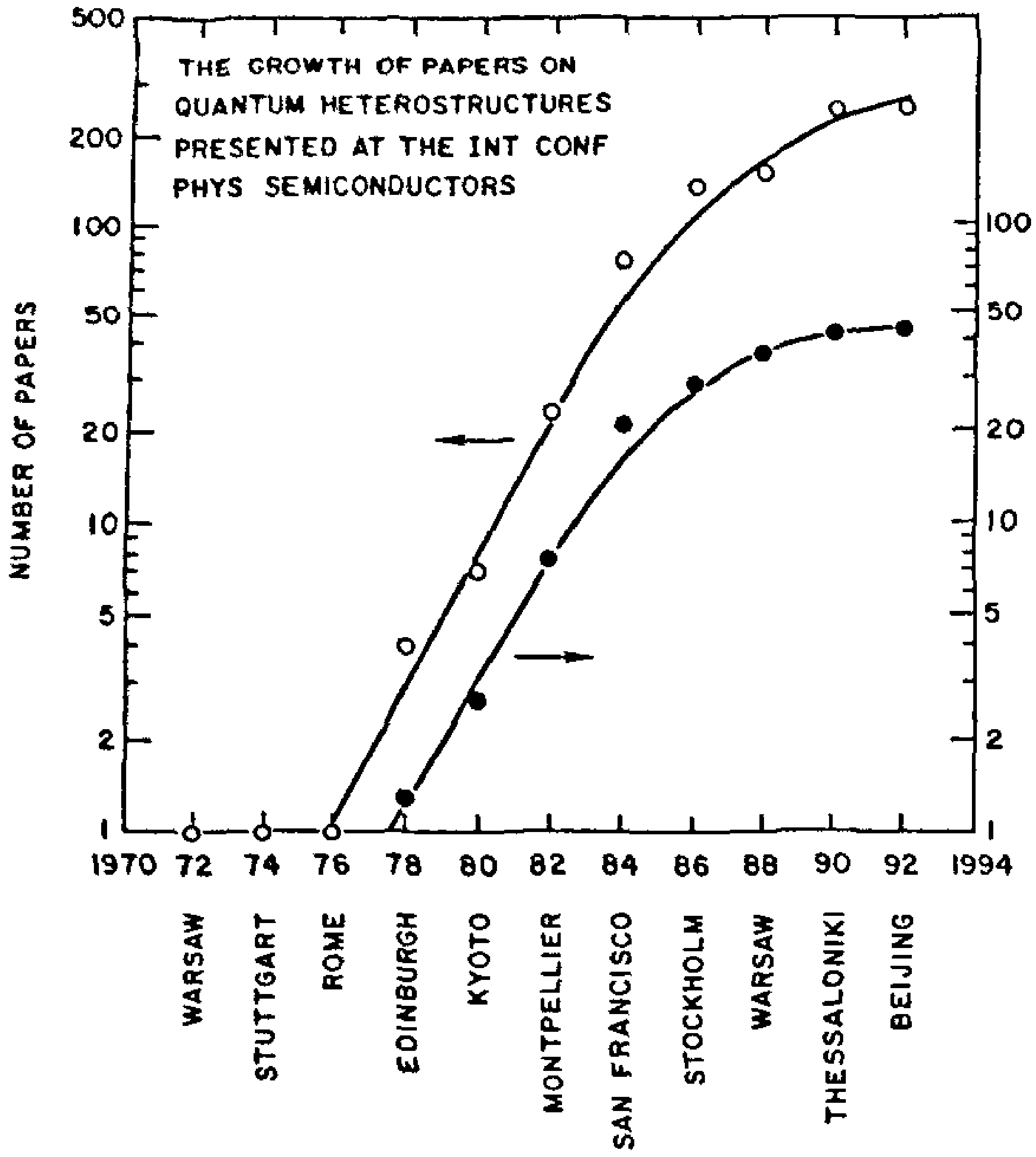

Figure 3. Growth in relevant papers at the biennial International Conference on the Physics of Semiconductors

history of one-dimensional mathematical physics, including the above-mentioned resonant tunnelling[3], Kronig–Penney bands[20], Tamm surface states[21], Zener band-to-band tunnelling[22], and Stark ladders including Bloch oscillations[7–9], all of which had remained more or less textbook exercises, could, for the first time, be practised in a laboratory. Thus, do-it-yourself quantum mechanics is now possible, since its principles dictate the details of semiconductor structures[23].

We have witnessed remarkable progress in semiconductor research of superlattices and quantum wells over the last two decades. Our original proposal[1] and pioneering experiments apparently triggered a wide spectrum of experimental and theoretical investigations on this subject. A variety of engineered structures exhibited extraordinary transport and optical properties which may not even exist in any natural crystal. Thus, this new degree of freedom offered in semiconductor research through advanced material engineering has inspired many ingenious experiments, resulting in observations of not only predicted effects but also totally unknown phenomena. As a measure of the growth of the field, Figure 3 shows the number of papers related to the subject and the percentage of the total presented at the biennial International Conference on the Physics of Semiconductors. After 1972, when the first paper[14] came on the scene, the field went through a short period of incubation and then experienced a phenomenal expansion in the 1980s. It appears that nearly one-half of semiconductor physicists in the world are working in this area. Activity in this new frontier of semiconductor physics has in turn given immeasurable stimulus to device physics, provoking new ideas for applications. Thus, a new class of transport and optoelectronic devices has emerged. In this interdisciplinary research, there have been numerous beneficial cross-fertilizations. I hope this article provides some flavour of the excitement associated with the birth of the semiconductor superlattice.

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