Issues in Nano-Photonics: Coupling and Phase in Resonant Tunneling

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Introduction:

Modern Nano electronics involves the use of heterojunctions in forming energy steps based on band-edge alignments in effecting quantum confinements. When the electron mean-free-path exceeds couple of periods, man-made quantum states appeared, mimicking natural solids with sharpness determined by the degree of coherence dictated by a relatively long mean-free-path. When a single quantum well is involved, the structure is represented by resonant tunneling. This process can further be extended to 3D (3-dimension), known as QD, for quantum dot, however, thus far only few systems have been found possible, mostly involving InAs, or InN. However, the real problem lies in I/O, making contact to a single quantum dot, seems to be impractical on account of difficulties in making contacts in Nano scale regime. The issue with impedance matching, is the most important aspect for efficient devices, whether as detectors, or as generator in frequencies between THz to visible light. As size shrinks to Nano-regime, even the wavelength of IR is too large for effective coupling to the quantum dots without some sort of coupling such as the use of Fabry-Perrot mirrors, which is in fact unsuited for quantum dots, unless these dots are arranged in an array mimicking a solid with translational symmetry, which in fact defeating the purpose of going to quantum dots, except when the distribution of these quantum dots are arranged either representable by some distribution functions suitable for arriving at a meaningful average, or periodically mimicking a solid, such as the man-made superlattice, SL, originally proposed by Esaki and Tsu. [1, 2]. Interestingly Esaki and Tsu were asked to remove the reference on doping in the barrier region for increased mobility by the reviewer for the IBM's own J. of Research and Development. We did protest to the Editor-in- Chief of the Journal to no avail! Because of this experience, it did occur to me of requiring something beyond the regular reviewing process in technical journals. Some ten years ago, I proposed to M. Henini the need to have a journal with two outlets for publications, one 'regular', and another as 'special': rejected by reviewer, but accepted by the editorial staff. For some reason, we did not get enough support then.

There is another important issue, RPA, Random Phase Approximation, coined by Bohm and Pines for overwhelming majority of physical interactions representable by the neglect of phase. For example, phase arrays depend on phase relationships between individual elements, or in this case, dots, identical to a dielectric function used to represent interaction with light. However, phase array antennas cannot work with RPA for transmission and receiving. Similarly, meta-materials and photonic crystals [3] utilize dielectric functions, or simply designed with the use of RPA. Therefore, it is important that RPA should be taken into consideration in the design of quantum photonic systems, particularly, for I/O and coupling. In fact, a good device expert would tell you that almost

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all devices are never solely represented by a single active component, rather, a composite of components such as the Quantum Cascade Laser, QLC, [4] having injector, active region for maximum selected interaction with light, and collector, for delivering the output to the next section in a serial design, including forming a parallel system, where the main path can be bypassed. I was asked to translate the concept of parallel computing back in 1972 to the visitors from the Chinese Academy of Sciences. As we know that Block oscillations in a superlattice, SL; was the main attractiveness for SL for providing THz devices. However, today, THz devices with QCL out-perform SL by a long shot! Also because the primary operating principle of band-gap by design involves Type II SL with InGaAsSb systems, more emphasis will be given to this topic in dealing with quantum sensing.

The main difference between classical systems represented by counting the individual parts, and waves by summing the density of states in reciprocal space, the **k**-vector space, which naturally merge into the consideration of RPA, Random Phase Approximation originated by Bohm and Pines. [5] These are the issues from the point of view of basic physics; however, to a good device engineer, such arguments may represent a good start, but never are fully sufficient and truly important, because all devices involve system or systems of individual components. When these individual parts are again interacting, then each individual entity again cannot be counted. Such complexity forms the daily concerns with an operating system. We are always led to concern of the whole system such that classifying parts that can be counted cannot represent the crux of the complexity, far more than the simple RPA in totaling interactions.

We must look into response time. For example, resonant tunneling has been numerically computed with the time dependent Schrodinger equation, roughly correct with a Guassian pulse for I/O near resonance. When input photon energy is different from a Gaussian, the build-up time, and decay time are quite different using the time dependent Schrodinger equation. And if the input light is not a plane wave with infinite wave train, time dependent computation must be adopted. System analysis teaches us the importance of impedance matching. However, take for example a system consisting of $\boldsymbol{E}$ and $\boldsymbol{H}$ waves of light as well as electron waves; do we simply match the respective impedances? Take GaAs lasers; the piezoelectricity of GaAs is sufficiently high to generate phonons. These issues are simply ignored, while with quantum dots, or meta-materials in general, both light and electrons need to satisfy boundary conditions. Imagine when photons and electrons are coupled forming a couple mode, one wonders whether separate boundary conditions on the wavefunction ψ for electrons and vector potential $\mathbf{A}$ for photons are fundamentally meaningful.

Lastly, quantum entanglement should not be taken seriously as an issue of quantum sensing, because the real world has unavoidable fluctuations. My view is that quantum entanglement becomes necessary consequences of Pauli's exclusion principle. If we accept zero point fluctuation, how then we can accept entanglement operating throughout the universe. It is easy for us to claim

that as long as we can adjust something for maximizing the intended signal, good experimental process can indeed take care of all these issues. However, it must be understood that one can be trapped in a local maximum without even realizing it.

The GaAs/GaAlAs Superlattice Story

The story leading to the successful introduction of GaAs/GaAlAs man-made superlattice is probably not known to most. Less than three years after I joined IBM working under the supervision of Leo Esaki, one day he called me to his office, representing something happening more and more after Leroy Chang went to MIT for a sabbatical. In fact Esaki had acquire some respect to my ability in dealing with the theoretical aspects of solid state physics after I successfully explained the mysterious Van der Pauw type [6] of experimental results with GeTe and SnTe. He showed me his idea in putting Esaki tunnel diode in series. My first question to him was whether they are put in series in a periodic way. The reason I asked this question leading to the idea of putting elements periodically, was because in 1966, just before I decided to go to IBM, I read the book by Brian Pippard, [7] where he discussed what happened to metals if the mean free path is sufficiently long, electrons under the application of a voltage would be moved toward the Brillouin zone boundary to be reflected resulting in oscillations. Pippard pointed out that it would never happen because the mean free path in metal is a million times too short to allow electrons reaching the Brillouin zone boundary. In fact Pippard showed how to arrive at the correct distribution function beyond the elementary ways used in deriving Ohms law treated in elementary books in Solid State. [8] Over the weekend, I presented to Esaki and our group my solution based on Pippard's simple equation showing the negative differential conductance, NDC, if the period of the "superlattice" being 10^3 larger than the real solids, so that the Brillouin zone is proportionally smaller allowing the electrons to reach the zone boundary to effect Bragg refraction. Without collision, Bloch Oscillations would result in pure oscillatory motion so that the average current would be zero, the cause of NDC. With scattering, there follows negative differential conductance. Since Esaki, the inventor of the Tunnel Diode appreciated what NDC means; he immediately started filing of patents, as well as urging IBM management to support such venture of man-made solids for electronic applications, with the name Superlattice. I objected this name and reminded Esaki that superlattice has been routinely used such as silicon carbide. Nevertheless, Esaki insisted that ours involves man-made periodic superlattice in configuration space and minizones in reciprocal space. Therefore, superlattice, short for SL, should represent what we proposed to do. After receiving token support from his manager R. Keyes at IBM, he successfully convinced ARO to support our work. Some details surfaced why ARO got so involved, accept the first two patents assigned to IBM, the subsequent ones were assigned to US Army because ARO supported the superlattice research at the beginning. Without ARO support, the idea would have been passed over! In those days all I remembered was that even my travel to Cambridge England for the 1969 Conference on Amorphous Materials organized by Sir N. Mott was paid by ARO via a special pass obtained from United States Military Academy at West Point. The

tittle of ARO contract administered by Charles Boghosian of the Physics Division of ARO, reads "Experimental and Theoretical Investigations on One-dimensional Periodic Potentials and Single Potential Barriers in Semiconductors." Some details of Superlattice Research at IBM, sponsored by ARO became known when Robert Luntz wrote a document 'The Superlattice Story' under the auspices of Mikael Ciftan, the Physics Division Chief at ARO, to be available for the White House serving as part of the Nano-Initiatives. In my view, working for both BTL and IBM, I believe that BTL might support highly speculative work, but not IBM. Without the role played by ARO, research on superlattice would not have been developed to what it is today!

Now, what material can we use? In fact no one under Esaki knew anything about crystal growth in 1969. Esaki asked Eugene Blakeslee to make a superlattice with GaAs/GaP, using both liquid phase as well as VPE, now called CVD. We built SL structures first shown in XRD, and then in TEM, even RBS, but no NDC, negative differential conductance was ever detected. Esaki and I went to BTL for help and learned that GaAs/AlAs, a system with closer lattice match developed for the improved efficiency of the GaAs laser, commonly known as the DH-laser, with DH for double heterojunction, would be the material. In other words, GaAlAs has wider bandgap, serves as charge confinement as well as trapping of light as in Fabry-Perrot interferometers. We were unsuccessful at IBM with the use of $GaAs_xP_{1-x}$, first tried by Gene Blakeslee. Even after we switched to $Ga_{1-x}\ Al_x\ As$ barriers, because we were using x = 0.5, our barriers were so strained and our exciton peaks for the quantized GaAs quantum well comparing with those at BTL is like night and day! [9] They had at least five years of head start on perfecting GaAlAs for the DH heterojunction GaAs lasers!

Something else should be mentioned regarding the perfection of stoichiometric III-V alloy systems. Basically luminescent spectra were used to optimize the growth of these ternary III-V alloy systems at BTL while Raman scattering were used at IBM. Accept few researchers at IBM, such as A. Onton and M. Lorenz, who worked on optical luminescence, we, H. Kawamura and I were using Raman scattering for the calibration of the alloy system. The reason why we chose Raman partly because I was fascinated with Raman, by choosing a sample of $Ga_{1-x}Al_xAs$ having x = 0 at one end of the sample and x~1 at the other end, sliced into 10 pieces with wet chemistry determination of the composition, used for standard. In this way, we, with L. Chang, developed a simple and fast turn-around for the MBE growth of the alloy system. However, real progress was made not until one day Al Cho told me that we should not have exceeded x = 0.3 in $Ga_{1-x}\ Al_x\ As$ system for the minimization of strain due to lattice mismatch.

Also I would like to mention something not known to most people engaging in superlattice research. My original formula for the negative resistance of SL using Pippard's formula [6] was considered by Peter Price as questionable. He suggested to me that his post-doctoral fellow, Paul Lebwohl, who just did a thesis using the Green function of the Boltzmann transport equation, might be able to get a more correct expression for the NDC, negative differential conductance, for the

superlattice. Paul and I soon launched a more involved calculation, [10] obtaining an expression for the NDC. As it turned out that the Green function using a set of infinite delta function located at all the Brillouin zone boundaries, lead to essentially similar results, while proving that Chamber's path integral is in fact exact! [11] It was by the use of the Chamber's path integral allowing us to obtain the time dependent current, consisting of all the higher harmonics involving the non-linear contribution to the superlattice, which also serves as the correct expression in considering resonant tunneling as well as NDC leading to THz oscillations. [12,13] What amounted to is the fact that as long as scattering is represented by a relaxation term, Chamber's path integral is exact for the solution of any dispersion with boundary conditions at infinite number of Brillouin zones. There is no need to involve Monty Carlo computations as pointed out by Peter Price. In fact when he showed me his results in some strange dimensionless plot, I converted back to current and field, which is identical to ours. He then admitted to me that for convenience, he used the same constant relaxation term as we did, and therefore, there should not be any difference, as proved by his postdoc Lebwohl! At this point I would like to comment something quite important as far as progress in a given technical field. Fundamental physics is important to support basic concepts and logic leads to certain results to support what we are after. One often hears that what is important is experimental verification. However, when further improvements are needed for the status of a given technology usually involving very detailed understanding, which is really not needed at the initial stage, proving the concept, involving no more than basic understanding. Therefore, detailed modeling is not necessary until the concept has been shown correct. Ai this point, intense engineering technology follows, which usually involves difficult mathematical and physical modeling.

I would like to mention something I learned from the masters. During Professor David Turnbull's retiring event, I showed him my laser annealing using the forth harmonic at 266nm of the Nd-YAG laser, which showed no rings, indicating that melting may not have occurred. Furthermore, I showed him a technique we developed by putting a transducer at the back to give a measure of the change of state from solid to liquid. Then I pointed out to him that even if melting had occurred, the melting point seemed to be much lower. He instantly said, "At 266nm, the absorption $\alpha \sim 10^6 cm^{-1}$would have given you two dimensional melting, which is 2/3 of the melting point. I said, "Wow, right on! Where did you publish that?" He replied, "I tried, but was rejected!" During the Industrial Affiliates Event at U. of Illinois, I asked Professor Bardeen about his 2/3 law for the good estimate of the Schottky barrier. He said, "All contacts are more or less two dimensional therefore the pinning of Fermi level is near 2/3 of the bandgap." I mention these rules developed by highly recognized theorists. And yet they would use very simple concepts for explanations. I am happy to be able to express these views, so dear to me during my years of research. Figures below showed the measured I-V and the computed I-V of a typical superlattice. It is this sort of result that provides confidence in what we are dealing with. Figure 1a and 1b show the measured I-V showing NDC, [14], and the computed using the expression given in [1,2].

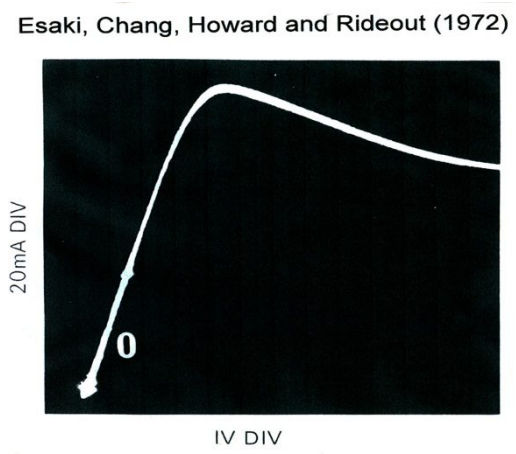


Fig 1a. I-V of GaAs/$Ga_{0.5}Al_{0.5}AS$ SL with 7nm period, showing NDC.

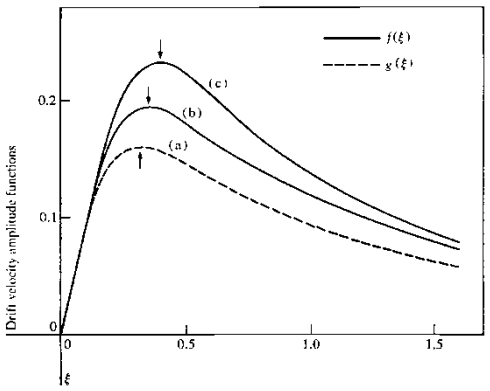


Fig 1b. Drift velocity versus reduced field parameter ξ ,(a) for sinusoidal potential (b) periodic square-well

Resonant Tunneling

Resonant tunneling, as described, was envisioned to counter the claim of Ian Gunn that the observed NDC was due to Gunn Effect with domain oscillation in GaAlAs turnery alloys, by reducing the quantum well region of the SL to a single well with two barriers on each side. I want to make some comments about the way it was theoretically computed. Naturally, one would try to find a way to compute using, for example, WKB approximate perturbation, or Bardeen's transfer Hamiltonian procedures described in Duke's book. I knew it cannot be done because resonant effect often means that one must compute to all orders. The very first calculation was based on the use of transfer matrix from section to section, and compute the transmitted using a computer. [15] However, when Stevens spent some time at IBM, he mentioned to me that it may be important to compute the time dependent resonant tunneling. Following Stevens procedure, Subrata Sen computed the time dependent tunneling through a single DB (double barrier). First, the Green function for the one-dimensional equation for the double barrier, DB, structure is obtained. Excitation functions are chosen for various cases: spatial distribution at t = 0, or specifying a time function at x=0, etc. The computation is very complex; however, some of the typical essential results are shown in Fig. 2. Note that at resonance, the rise is smoothly reaching an over-shoot. However, farther away from resonance, rapid oscillations, in some way may be misinterpreted as instability in experiments! It is interesting after the excitation is cutoff; decay is not monotonic, rather rapid oscillatory decay as shown. It is evident when the excitation is cutoff before reaching the maximum; the transmitted current is proportionally reduced. *The maximum buildup time is ~ 200fs, which explain the fast device speed greater than THz.*

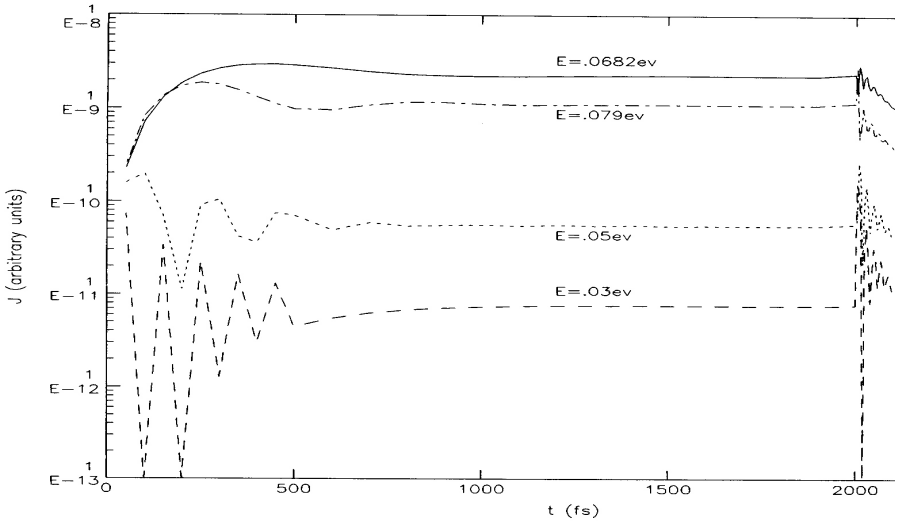


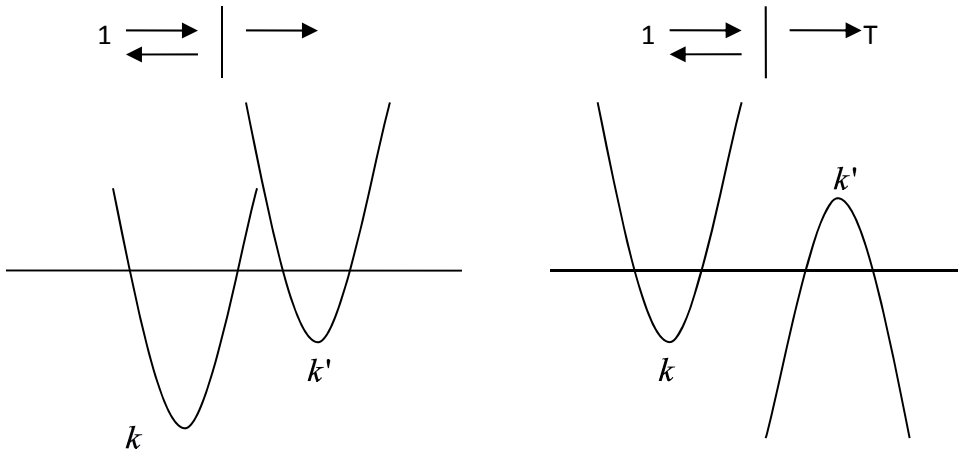
Fig. 2. Transmitted current J versus t in fs for GaAs well width w = 6nm, and GaAlAs barrier b = 2nm, The energy of resonance is E_4 = 0.0682eV, and E_3 = 0.079eV, E_2 = 0.05eV, and E_1 = 0.03eV. First appeared in Tsu [17,19] taken from Sen's unpublished thesis [16]

The computed value of the build-up time at resonance from Fig. 2, or using the estimate is ~ 200fs, which is considerably shorter than these computed values of several ps obtained by, for example Gong et al [20], and others, cited in Gong's work using time dependent Schrodinger equation, but assuming variable separable in both spatial and time coordinates, without the procedure established by Sen [16], using Green function to include the initial value in space. This discrepancy of a factor of 30 dictates further study in detail. Our initial assessment points to the fact that all variables including space and time assumed to be separable may be incorrect.

Quantum Structure with Type II Alignment

Originally Esaki and I were looking for a way to move the point of inflection where the effective mass changes sign, closer to the Brillouin zone center, possibly will result in NDC at lower applied voltage. Esaki asked me what would happen with InAs and GaSb, or more generally with taking issue of strain, with $In_{1-x}Ga_xAs$ / $GaSb_{1-y}As_y$ system, where it is known to have band-edge alignment in such way that the conduction band minimum in one would be below the valence band maximum of the other. I replied that I would look into it; however, it seemed that two bands crossing would result in splitting in forming new bands. I usually try out my views with Ted Schultz, a first class theorist and my tennis partner. When I stated the problem to Ted while Allen Fowler was talking to Ted. Allan said that, "It is a typical high school problem, because electrons from the valence band would go to the lower conduction band results in semimetal." I replied, " Not so fast, the U-part of the wave function of valence band are orthogonal to conduction band, thus preventing them from mixing, unless linear combination results from coherent interaction, as in the formation of bonding and anti-bonding states in molecule." At this point, Ted said, "Ray, you have got an

interesting problem on hand!" Since the Type II system is so important in current IR detectors and quantum sensing, [18] I shall point out few salient points about this type of heterostructure. When are the full Bloch waves needed? Figure 3(a), following [19], shows a type I-superlattice, i.e. an electron in a conduction band incident to the left of another conduction band separated by an interface and a type II-superlattice in (b) where the right side is a valence band at the same energy.



(a) Type I (b) Type II

Figure 3 *E–k* for (a) type I and (b) type II superlattices, with energy at horizontal line

Explicitly, [19] the superscripts (+) and (–) denote the waves moving to the right and left respectively, and the subscripts c and v denote the conduction and valence bands, or the upper and lower bands:

$$\psi_c^+ = U_c(k,x)\,e^{ikx}\,, \qquad \psi_c^- = U_c(-k,x)\,e^{-ikx}$$

$$\psi_v^+ = U_v(-k',x)\,e^{ik'x}, \qquad \psi_v^- = U_v(k',x)\,e^{-ik'x}\,. \tag{1}$$

Let us proceed with the reflection problem, with an electron from the left conduction band and emerging from the right of the interface into the conduction band with (+) for k_2, and valence band with (–) k_2. The conduction band electron incident from the left onto an interface located at x = 0, we use $U_1 \equiv U_c(k_1, x)$, $V_1 \equiv U_c(-k_1, x)$; and for the transmitted electron to the right, $U_2 \equiv U_v(\mp k'_2, x)$, (-) for movement to the right and (+) for movement to the left, then,

$\psi_1 = U_1 \exp(ik_1x) + R\,V_1 \exp(-ik_1x)$, and $\psi_2 = T\,U_2 \exp(ik_2x)$. Matching these wavefunctions and their derivatives and for equal effective masses

$$R = \frac{(k_1-k_2)-i[(U_1'/U_1)-(U_2'/U_2)]}{(k_1+k_2)-i[(U_2'/U_2)-(V_1'/V_1)]}, \quad \text{and} \quad T = \frac{2k_1-i[(U_1'/U_1)-(V_1'/V_1)]}{(k_1+k_2)-i[(U_2'/U_2)-(V_1'/V_1)]}\,. \tag{2}$$

Therefore, for Type-II, the traditional reflection coefficient R and transmission coefficient T involve the log derivatives of U and V Bloch functions. Generally, Bloch waves should be used. The smaller the period, the larger is the interaction resulting in coupling and larger bandgap. Therefore Type-II gives rise to band-gap by design. However, if the period > coherent length, the system returns to semi-metallic, carriers are transferred through diffusion. Obviously for plane waves, these *U* functions do not appear in R and T. Therefore, some algebra is involved resulting in R and T once the basis states | 1 ⟩ and | 2 ⟩ are chosen.

Type II superlattice with Bandgap by Design

Writing the Bloch function $\psi(k,x) = U(k,x)e^{ikx}$ for the wave going to the right, and $\psi(-k,x) = U(-k,x)e^{-ikx}$, for the wave going to the left, then the waves in each sections are

$$\psi_1(k_1,x) = [A\ U_1(k_1, x)\ \exp(ik_1x) + B\ U_1(-k_1, x)\ \exp(-ik_1x)], \qquad 0<x<d_1 \tag{3}$$

$$\psi_2(k_2,x) = [C\ U_2(k_2, x)\ \exp(ik_2x) + D\ U_2(-k_2, x)\ \exp(-ik_2x)],\ d_1<x<d_1+d_2=d \tag{4}$$

$$\psi 3(k_3,x) = \psi_1(k_1,x-d)\ \exp(ikd)\ . \qquad d<x<d_1+d \tag{5}$$

Assuming each layer thickness is an integer multiple of the lattice constant *d,* the *E-k* relationship for k as a function of *E* results,

$$\cos(kd) = \cos(k_1d_1)\ \cos(k_2d_2) - F\ \sin(k_1d_1)\ \sin(k_2d_2), \tag{6}$$

in which

$$F = \frac{1}{2}\left[\frac{ik_1 + U_1'/U_1}{ik_2 + U_2'/U_2} + \frac{ik_2 + U_2'/U_2}{ik_1 + U_1'/U_1}\right] \tag{7}$$

where $U_i = U_i(k_i,0)$, and $U_i' = dU_i(k_i,x)/dx\,|_{x=0}$, and the allowed bands correspond to energy with real *k*. (6) and (7) reduce to the well-known Kronig-Penney solution if the logarithmic derivatives in (7) are zero. Some of the details in calculating the *E–k* from the above equations have been left out in the published version, [21] I handed over my finished theoretical work
using *k.p*, but requiring fair amount of computation to Sai-Halacz before I left IBM for Campinas Brazil at the start of 1977. The results with LCAO by Sai-Halasz, Esaki and Harrison [21], expanded into three-dimension but left out the self-consistency and spin. In fact LCAO led to the same results as the use of *k.p*. as shown in my book [19]. Figure 4 shows the computed E-k for the two-band k.p in [21].

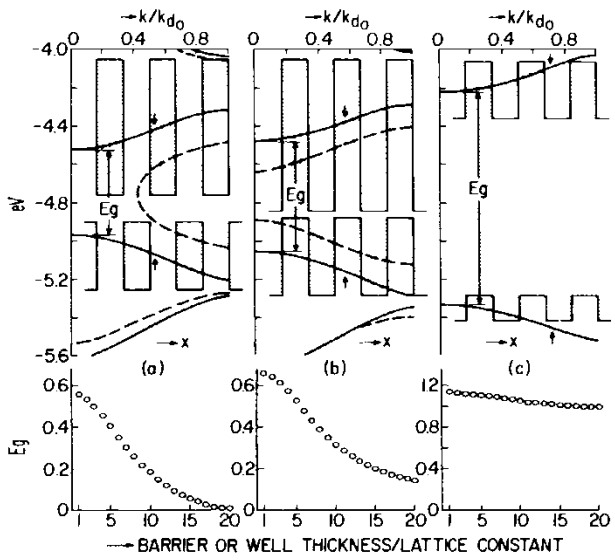


Figure 4 The *E–k* relationships calculated by the two-band k.p. model, top of figures and energy gap, bottom of figures, versus the reduced $k/(\pi/d)$, for three pairs (a), (b) and (c), together with their respective band-edge profiles. Dashed curves show the wrong results from plane waves.

For more detail of understanding the case of Type II superlattice, Fig. 4 shows clearly that plane waves, without the U-part of the wave functions represented by dashed are clearly incorrect. What is interesting is the fact that except using plane waves where $|1\rangle$ and $|2\rangle$ are constants, any such orthogonal pairs as $|1\rangle = (g/\pi)^{1/2}\cos(gx)$ and $|2\rangle = i(g/\pi)^{1/2}\sin(gx)$, with $g = 2\pi/a$, can yield similar energy bands as shown in Fig. 4. There are some very instructive issues discussed in detail in reference [19], for example, our simple procedure based on the k.p computation of the band structure is almost identical to those computed by Harrison. [21]. At this stage I want to emphasize that it is not surprising the precise results are not so sensitive what kind of basis set such as $|1\rangle$ and $|2\rangle$ used, as long as these two are orthogonal in the range of the reciprocal space $g = 2\pi/a$. Most experimental results involved simply cannot distinguish the small discrepancy of any particular matrix element $\langle 1|k.p|2\rangle$, because the main effect in experiments involves the delta function part of the interaction which is sensitive to the conservation of the energy of the incident photon and the bandgap of the system. Insensitivity of the bandgap to any precise representations $|1\rangle$ and $|2\rangle$, is really generally accepted for the k.p representation. In fact this is why k.p procedure is so popular with those who engage in optical characterization of a given material. Therefore, more precise measurements as to the polarization dependence with respect to the crystal orientation may reveal more subtle properties in Type- II devices.

Some Useful Issues for Quantum Devices as Sensors and Amplifiers

- All devices are in fact in component-forms. Even a simple resistive switch has input and output, serving as a three component structure: Input – Active – Output. For example, we all agree that injection laser has at least three parts such as I – Optical – O. A MOSFET has two for the source-drain and two for the gate oxide, even the Ovonic chalcogenide switch has four parts, two for the I-O and two for the control pulse to turn it on-off with pulses. RTD has I-O plus the active layer with man-made quantum state. Thus, the original Bloch oscillator of the man-made superlattice, seemed to be a man-made solid, however, in reality, as an active device, it is used as components, and therefore, also should be treated as part of a device. *I do not know what precisely was on Esaki's mind, but I can tell you that I was not clear on that point until quantum cascade lasers beginning to show real success in the world of devices!* Even a silicon photo voltaic cell has quite a few parts. The main part absorbs the light and converts it to mobile electrons. These electrons are collected by something one cannot easily see, ITO, In-Tin Oxide, fairly transparent with poor transport property, yet good enough to transport the collected electron to the bus-line, generally copper lines. When you see a typical PV panel, you cannot see the ITOs, only the copper lines. So that you do not know how the collected electrons can travel so far to reach the main contacts. All detectors have at least three parts. Photoconducting detectors have I-O plus the part interacting with the incident light. However, in general, there are more, because we should also count the Bragg refractors.

- As with circuits, we are familiar with two types of connections, in series and in parallel. We must realize that circuit theory is basically one-dimensional system, I – A – O. Discovery made by van der Pauw of using any 2D surface for four contacts revolutionize measurements of impedances. However, conformal mapping is not possible with three dimensional object, therefore, most of our devices either purposely avoid 3D or at least having interaction involving 2D or 1D combinations. In fact the complexity involving in 3D-wiring is still never used in most individual devices, except in communications , for example, connecting to high-rise buildings.

- I remember when I first went to Campinas, the Director of Institute of Physics, Jose Ripper told me to collaborate with Phillippe Brosson, who came from Thompson CSF, France, was building an all electronic acquisition system for spectroscopy. Imagine, in 1977, he had a CCD system build up for his grating, instead of turning as most of the spectrometers, his grating is fixed as the old spectroscope having a scanner with a CCD, collecting data in one shot for the whole spectrum!

- All detection systems utilizing resonance for matching, requiring long trapping for build-up, as well as slowing down the response. You cannot have something for nothing. Fast response should not involve resonance! However, there is a simple principle; system in series slows down the process, and speeds up in parallel. In other words, if you cannot beat it in a given system, try putting systems in parallel in a phase coherent manner. The technique applied to multi-antennas linked together in a phase array is a good example. In fact, I was deeply involved at BTL involving a chirped ultrasonic system by accident, which reminded me that phase in interacting systems may be manipulated into systems beating the usual adverse phase interference.

- I should discuss what constitute boundary conditions. For atoms located at a set of positions, the wave functions at these points must be specified, because the density at these points are specified. However, the current, something proportional to the derivatives, must also be specified. These specifications constitute boundary conditions for ψ and ψ' which lead to n × n diagonalization for the eigenvalues determinations. Because statistics are always involved whenever the space is no longer, in mathematics sense, analytic; some averaging procedures must be adopted. There are several ways: averaging the probability density, with the wave functions, or even averaging the derivatives, or both. Which is correct depends on the situations. If the interactions involving k.p, the average derivative is more important, while in diffusion, it is clear that the average density is more important. These considerations are very important dealing with quantum dots. My intuitive judgement is to average both the wave functions and derivatives separately.

- We can assign a damping in time by the introduction of a term $e^{-\alpha x}$ in spatial damping and $e^{-\gamma t}$ in time damping. However, we can introduce damping directly into the wave equations [19] as done by Langevin, i.e. involving a first derivative in spatial coordinates, commonly known as braking. However, it is very interesting that when a Langevin damping is introduced into Schrodinger equation, the Green function G is now complex. And since the $\mathcal{Im}\ G$ is proportional to the density of states, damping means losing to the uncollectable world, the DOS moves up in energy. Before Sir N Mott passed away, I showed that to Mott, and convinced him that when damping occur in amorphous Si, *n(E)* moves up by 0.1eV, in the neighborhood of his mobility gap. Now we may ask what happens to interaction with the zero point fluctuation such that the $\mathcal{Im}\ G$ moves up in energy. We know that is correct because what moves up due to interaction with the zero point fluctuation is precisely the cause of Lamb shift. This shows that Lamb shift is originated in any oscillating system such as the Schrodinger electron affected by the background fluctuation such as using the second quantization, resulted in moving up the energy spectrum. Interestingly, the part of the energy spectrum with the largest upshift is at the highest density of states. [19]

- Physics as we know depends on constitutive equations, such as dielectric function, conductivities as well as the elastic constants and thermal expansion coefficient, etc. We use these to handle interactions. However, interaction is what physics is all about, and only quantum mechanics can describe interaction in terms of the most fundamental potentials. Classical potential describing interactions has no phase, therefore, cannot describe wave, which can add and subtract, such as describing by wave motion. There is no way to describe interaction without QM when waves are involved!

- I need to include the proper wave impedance and bring in the dimensionality. One-D system would uniquely define impedance function, in terms of fundamental $G = e^2/h$, however, in 3D solid, because of translational symmetry, there will be fractions whenever, $l, m, and\ n$ are distinct. However, in free apace, translational symmetry is arbitrary, and therefore, fractions should not occur in this fundamental G! [23] & [19]

- I shall discuss the role of Type II alignment with and without coherence. With coherence, we would have opening up of new energy gaps, with bandgap by design! However, if the layers are much thicker than the distance for coherence, or mean free path, then, we would have transfer of valence band electrons into the lower conduction band at an adjacent layer, in such way that valence band electron would be transferred to the nearby lower conduction band, resulting in doping quite similar to modulation doping. In fact such cases are commonly occurring involving dipolar catastrophe in recently discovered high mobility at carrier concentration above the solid solubility limit. [24] In fact, this type of occurrence appear particularly in Si due to the oxide gate, has led to so much mysteries for many years, including the strange conductor oscillations, including hysteresis in Si quantum dots, first reported years ago by Quiyi ye. [15] it appears that many strange effects in the past, including the famous 1/f noise, may finally be explained.

- Some recent contributions: Pulling electrons from GaN: Tsu Sonic amplifier: Henini et al, [19] and Paul Burger's resonant tunneling and Esaki tunneling combination.[26]

- Why do we go for quantum devices as detectors with SL and Particularly with Type II, instead of mixing the alloy compositions? What is the difference between GaAlAs alloy, and GaAlAs SL? The former would have some averaged bandgap, while the latter would have huge increase at the high joint DOS! OK. In the alloys, some averaging process has been applied by nature, while in SL, particularly with Type – II SL, in phase interaction leading to high joint density of states is why we are excited about. Now we form quantum wells by adjusting the well size. However, we cannot go below the original bandgap, to go into IR. So we use the overlapping InAs/GaSb system to have tunable bandgap starting from zero, when phase incoherent processes take over. That was the spirit with the overlapping SL called

Type-II SL where the effective bandgap starts from zero! However, originally Esaki and I wanted to move the point of inflection from somewhere near the zone boundary to the zone center. *That brings about some very interesting facts of life, particularly in dealing with new discovery, which is always not formally intended!*

References:

[1] Esaki,L.,Tsu, R.,IBM Research Note RC2418 (1969)

[2] Esaki,L.,Tsu, R.,IBM Res.Develop 14,61 (1970)]

[3] M.A. Fiddy, M.A., and Tsu, R. Waves in Random & Complex Media, **20**, 202–222 (2010)

[4] Faist, J. et al. Quantum cascade laser. Science 264, 553–556 (1994).

[5] Nozières P., and Pines D., Phys. Rev. 111, 442 – 454 (1958)

[6] van der Pauw, L.J. *A method of measuring specific resistivity and Hall effects of discs of arbitrary shape,* Philips Research Reports **13**, 1–9 (1958)

[7] Pippard B. *Dynamics of Conduction Electrons*, Gordon and Breach Science Pub. NY(1965)

[8] Kitel, C., *Solid State Physics*, John Wiley & Sons 1953.

[9] Dingle, R., Wiegmann, W., Henry, C.H., Phys. Rev. let. **33**, 827 (1974).

[10] Lebwohl, P.A., Tsu, R. J.Appl Phys. **41**, 2664, (1970)

[11] Chambers, R.G., Proc. Royal Soc., London, A**65**, 458 (1952)

[12] Tsu, R. , Esaki, L. Apply Phys Lett. **19**, 246 (1971)

[13] Tsu, R., SPIE **1361**, 231(1990)

[14] Chang, L. Esaki, L., Howard, W., & Rideout, V., Proc. 11th ICPS, Warsaw, p.431 (1972).

[15] Tsu, R. , Esaki, L. Apply Phys Lett. **22**,562 (1973)

[16] Sen, Subrata, MS Thesis, *Time Dependent Solution in Double Barrier Resonant Tunneling*, Dept. Electrical Engineering, A&T State University (1989)

[17] Tsu R., Nanotechnol 12, 625 (2001)

[18] Razeghi, M. *Proc. of SPIE* **6940** 694009, (2008).

[19] Tsu, R., *Superlattice to Nanoelectronics*, Elsevier, (2011)

[20] Gong, J., Liang, X.X., & Ban, S.L., Phys, Stat. Sol. (b) **244**-6, 2064-2071 (2007)

[21] Sai-Halacz G.A.,Tsu R., and Esaki L., Appl. Phys. Lett., **30**, 651(1977).

[22] Sai-Halasz, G.A., Esaki, L., and Harrison W.A., Phys. Rev. B **18**, 2812 (1978).

[23] Raphael Tsu and Timir Datta (2008) "Conductance and Wave Impedance of ERlectrons". Progress in Electromagnetics research Symposium, Hangzhou,China, March 24-28 Pdf (http://piers.mit.edu/piersproceedings/download.php?file= cGllenMyMDA4a…)

[24] Sitaputra, W., and Tsu, R., Defect induced mobility enhancement…Appl. Phys. Let. **101**, 222903 (2012)

[25] Ye, Q.-Y., Tsu, R., Nicollian, E.H. Phys. Rev. B**44**, 1806 (1991)

[26] Berger, P., and R. Anisha, *Comprehensive Semiconductor Science and Technology*, edited by Pallab. Bhattacharya, et al., Elsevier, V5, Chapter 13, 176-241 (2011).

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