

Nobel Prize in Physics 2000, how Silicon lost its groove.

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March 16, 2016

Abstract

In 1957 Herbert Kroemer published a paper entitled “Quasi-Electric and Quasi-Magnetic Fields in Non-Uniform Semiconductors”³. In it he expressed the utility of non-uniform semiconductor alloys in exploiting their natural atomic potential gradients to imply quasi-electric fields. The breakthrough in Modulation Doped Field Effect Transistors (or MOD-FETs) came from the ground-breaking work done by him and Zhores Alferov on Semiconductor hetero-structures that utilize these very fields. I will examine just Herbert’s findings.

1 Introduction

Let’s begin by first reviewing conductivity in metals and the partnership between electrons and electron-holes. It is common knowledge that electric current is made up of moving electric charge. We say a material is more conducive to electric current if external stimulus can excite its valence electrons to transition to the conduction energy band. Metals for instance are highly conducive because they have a surplus of valence electrons that live very close to the empty conduction band; therefore at the prompting of an external electric field are able to transition, inducing a current. Consider next the effect a constant external electric field has on the energy band structure of a homogeneous semiconductor. See 1. Note that the effect an electric field has on an electron is reversed for a hole. We can think of electrons and electron holes as particles that fall in opposite directions. Now notice in diagram (a) of 1 that the external electric field changes the energetic topology of the valence band (where the electron holes live) and the conduction band (where the electrons live) identically, such that the charged particles experience a gradient and begin to fall, electrons to the right and the holes to the left. Recalling,

$$F = q * E$$

we can see by integrating both sides,

$$\Delta U = q * \Delta V,$$

thus the change in electric potential energy is linearly proportional to the change in electric potential. With electrons losing the same amount of energy that holes gain over the same change in electrostatic potential.

Now, in Quantum Mechanics we know that the momentum of a particle in a well is,

$$p = \frac{\hbar k}{2\pi}, k = nL$$

(L being the size of an atom); and the Energy of bound particles is quantized. It follows that a solution for an electron in a periodic potential (2) is in order, the derivation of which happily lives in chapter 15.1 of Solid State Basics³. However a simpler version of this is derived in chapter 11.23, it gives the dispersion relation between energy and momentum states in allowed energy bands:

$$E = V_o - 2t * \cos(kL)$$

see 3, with V_o being the potential energy required for an electron to sit on a particular atom in the periodic potential, and t the energy required for an electron to hop to another nucleus. This dispersion curve is critical for determining the conductivity of a material since the allowed energies and momentum's available to the conduction band are characterized by this equation. Because of the periodic nature of the result, the allowed k-states for any band are bounded to a equivalent width of $\frac{2L}{\pi}$ see 4. Adding up the momentum for the top diagram in 3, we see that no current flows because the sum of momentum's is zero, and from the bottom we see that a current inducing electric field has the effect of shifting the momentum states such that their total sum is non-zero. Returning now to 2, it is clear that the application of a strong enough electric field increases the availability of the whole spectrum of states. Alas, electrons aren't the only charge carriers we will be dealing with. Electron-holes, so named because they are the vacancies electrons leave behind when they transition to the conduction- or any higher band, move with opposite polarity in the valence band. As a result, an external electric field has the pleasant outcome of inducing currents of both electrons and their remnant holes.

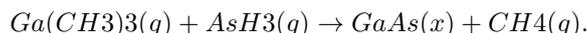
Now in diagram (b) and (c) of 2 we see that the topology of each band can be augmented independently. These simple looking alterations in actuality open up a world of possibilities for semiconductor technology. This is precisely the conclusion offered by quasi-electric fields arising from hetero-structures; the manipulability of electron band structure to the end of harnessing electric current.

Recall the Schrödinger equation³ in 5. The atomic periodic potential of each atom in the in-homogeneous semiconductor is represented as being a varying function of the position vector x . Since the varying atomic potential in the conduction band differs from the valence band, this equation becomes mathematical evidence that quasi-electric fields exists.

Now let's briefly review the generic homogeneous constant gap transistor. This transistor is typically constructed from a crystalline alloy which is doped with an excess of electrons (n-type) or electron holes (p-type). This gives rise to two varieties of transistor, the npn and pnp, so named to indicate the order of doping of the alloys used in construction and subsequently the order of their junctions. The order of the n's and p's implies one other thing about the structure of the transistor: what alloy is used as the collector, base, and emitter. In an integrated circuit the constant gap transistor is used as a logical element regulating the flow of current from the collector to the emitter through an applied electric potential to the base (called a gate); it goes by the classification, bipolar junction transistor. For the transistor in 6 we see the electron

band structure of the three regions. Paying close attentions to the gap energy between the conduction and valence bands – or equivalently the potential difference between the bands – we should notice that the separation is constant throughout. This means that the whatever electric potential we apply at the gate shifts the energies of both bands equally. This equivalence of potential gradients in both bands implies that the magnitudes of both currents are identical. Another application, one that I believe illustrates the utility of transistors and an area that has been most impacted by semiconductor heterostructures, is amplification. So far we have ignored the differing degrees to which we can dope the crystalline alloys we are implementing. Addressing this now, we should recall the restrictions the dispersion from 2 imposed on the energy band structure of a material. Namely, for any given band there are only a limited range of momentum states, and a corresponding upper limit to the number of electrons which can occupy them before the sum of their momentums vanish, along with current. It follows that this quality of semiconductors limits the extent to which we can dope our crystalline alloys. If we add too many electrons or electron holes we risk filling our conduction band to its limit and turning our conductor into an insulator. This is as we shall see, a big problem in constant-gap amplification. In 7 we see a bipolar junction transistor with an additional electric potential applied to the collector lowering it below the emitter. That said, the amplification of the transistor hinges heavily on the relationship between base and emitter, namely on the ratio of minority injection current over total emitter current. This ratio 9, represents the emitter efficiency which is proportional to the emitter amplification factor $\alpha_c e$. Combining the equation for the base amplification factor $\alpha_c b$ 8, with the emitter efficiency gives 10. It follows that the only way to improve the amplification factor of the base is to increase the emitter current, by heavily doping the emitter, but as we have just learned, we cannot dope to our heart's content! Herbert Kroemer's solution to this problem?– the Wide-Gap Emitter, 11. Notice the difference in potential gradients induced along the conduction and valence band edges at the junction. The severity of these slopes indicate that the emitter efficiency can be optimized without the use of dopants. Effectively paving the way through the insulating ceiling on amplifiers. I would say this is by far the most impactful discovery of the century!– And for how it has transformed Silicon valley, most notably Nobel prize worthy.

The materials of choice, so it would seem for most if not all high-electron-mobility transistors (HEMTs) or MODFETs are Ga, Al and As. These materials form the alloys GaAs, AlAs, and AlGaAs. These alloys stand out because their lattice constants are essentially the same³. The benefit of using alloys with nearly the same lattice constants is for growing crystals of GaAs, AlAs is the ideal substrate to grow GaAs on because there is a low probability that discontinuities will appear during the growing process. Further, as there are more than a few ways to grow GaAs and AlAs, I decided that Chemical Vapor Deposition was the best. A typical reaction looks like:



The process begins when the reactants sail in on carrier gas currents toward the surface of the Group 3-5 semiconductor, in our case AlAs. Near AlAs they undergo a gas-phase reaction where the GaAs forms and sticks to the surface

via chemisorption and the CH₄ is blown away. What's noteworthy about this process is that once everything is said and done, none of the Methane remains.

2 Figures

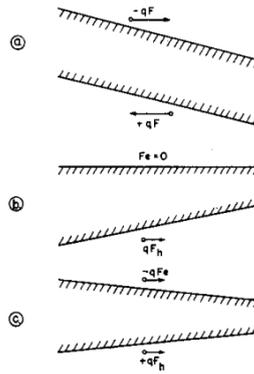


Figure 1: H. Kroemer, “Theory of a Wide-Gap Emitter for Transistors,” Proc. IRE, vol. 45, pp. 1535-1537, 1957.

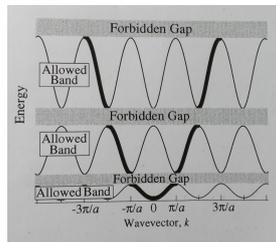


Figure 2: Simon, Steven H. The Oxford Solid State Basics. Oxford, United Kingdom: Oxford University Press, 2013. Print.

3 References

H. Kroemer, “Quasi-Electric and Quasi-Magnetic Fields in Non-Uniform Semiconductors,” RCA Review, vol. 18, pp. 332-342, 1957.

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H. Kroemer, “Band Offsets and Chemical Bonding: The Basis for Heterostructure Applications,” Physica Scripta T68, 10-16, 1996.

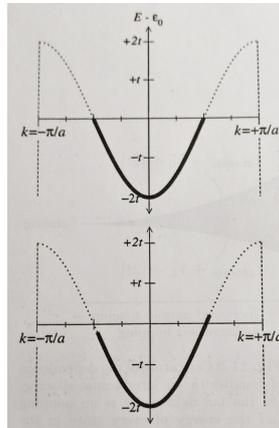


Figure 3: Simon, Steven H. *The Oxford Solid State Basics*. Oxford, United Kingdom: Oxford University Press, 2013. Print.

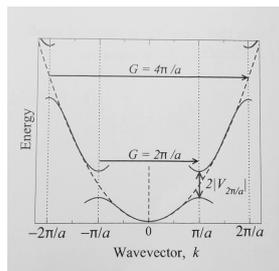


Figure 4: Simon, Steven H. *The Oxford Solid State Basics*. Oxford, United Kingdom: Oxford University Press, 2013. Print.

$$\left[-\frac{\hbar^2}{2m^*} \nabla^2 + E_B(\vec{x}) \right] \Phi(\vec{x}) = E\Phi(\vec{x}),$$

Figure 5: H. Kroemer, "Quasi-Electric and Quasi-Magnetic Fields in Non-Uniform Semiconductors," *RCA Review*, vol. 18, pp. 332-342, 1957.

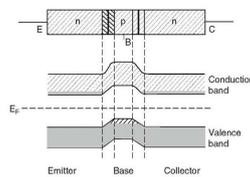


Figure 6: "Semiconductors (Electrical Properties of Materials) Part 5" what-when-how. <http://what-when-how.com/electronic-properties-of-materials/semiconductors-electrical-properties-of-materials-part-5/>. Web. 16 Mar. 2016

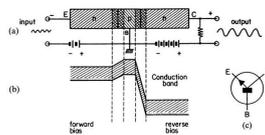


Figure 7: "Semiconductors (Electrical Properties of Materials) Part 5" what-when-how. <http://what-when-how.com/electronic-properties-of-materials/semiconductors-electrical-properties-of-materials-part-5/>. Web. 16 Mar. 2016

$$\alpha_{cb} = \frac{\alpha_{ee}}{1 - \alpha_{ee}}$$

Figure 8: H. Kroemer, "Theory of a Wide-Gap Emitter for Transistors," Proc. IRE, vol. 45, pp. 1535-1537, 1957.

$$\gamma = \frac{j_e}{j_b + j_e}$$

Figure 9: J_e is emitter current, and J_b H. Kroemer, "Theory of a Wide-Gap Emitter for Transistors," Proc. IRE, vol. 45, pp. 1535-1537, 1957.

$$\alpha_{cb} = \frac{\frac{j_e}{j_b + j_e}}{1 - \frac{j_e}{j_b + j_e}}$$

Figure 10: J_e is emitter current, and J_b is base current. H. Kroemer, "Theory of a Wide-Gap Emitter for Transistors," Proc. IRE, vol. 45, pp. 1535-1537, 1957.

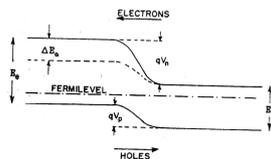


Figure 11: H. Kroemer, "Theory of a Wide-Gap Emitter for Transistors," Proc. IRE, vol. 45, pp. 1535-1537, 1957.