

## Development and Applications of Acoustic Charge Transport

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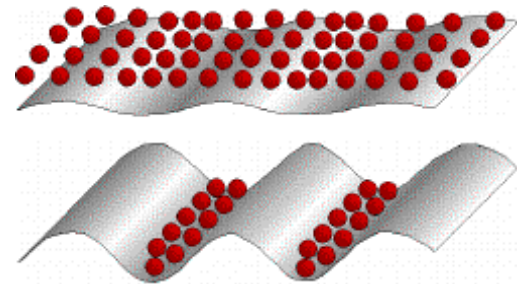
## Abstract

Acoustic charge transport is accomplished through the use of a surface acoustic wave passing through a low dimensional electron layer. The power efficiency is increased with a piezoelectric substrate. Quantum wires are formed with higher wave intensity, and quantum dots are formed with the interference of two waves. Such methods have applications in electronics. Excitons are preserved for longer times with the use of an acoustic charge transport system, which allows for the development and implementation of optoelectronic delays and storage devices.

A common goal of much of today's technological development is finding ways to make existing technology smaller or more efficient. This is especially apparent in electronics, where a constant push is made to make devices smaller, lighter, and more powerful. Acoustic charge transport (ACT) is a relatively new concept and technique which has applications in both electronics and optoelectronics, which uses light instead of electricity. Not only does ACT have applications in these areas, it has distinct advantages by being smaller and more efficient than currently employed systems.

Acoustic charge transport, as the name suggests, is the moving of charge through the use of acoustic waves. The charge that is transported consists of electrons forming a low-dimensional layer, residing in a semiconductor film called a quantum well. The layer of electrons is called low-dimensional because it forms a quasi-two-dimensional electron system, a layer of electrons so thin that the third dimension is negligible. To perform ACT, a sound wave, called a surface acoustic wave (SAW) due to its propagation in two dimensions, is passed through the semiconductor film. Properties of the semiconductor result in an acoustoelectric interaction in which electric field waves corresponding to the acoustic waves are generated by the piezoelectric effect. The piezoelectric effect occurs when pressure exerted on certain crystals causes them to generate an electric field. Sound waves traveling through the semiconductor travel in pressurized fronts, forming corresponding electric field waves. These waves form something analogous to a corrugated surface existing in terms of electric potential instead of space. The electrons are drawn toward the "troughs" in the electric field wave by electric forces just as ball bearings are drawn toward the troughs on a corrugated surface by gravity. As the wave moves through the semiconductor, it draws the electrons with it: an electrical conveyor belt pulling the electrons along the semiconductor.

ACT was first demonstrated in 1976 on a layer of silicon.<sup>1</sup> However, for some time it was an inefficient method of moving electrons. Due to the low piezoelectrical properties of the semiconductors used, much of the acoustic energy was not converted to an electric field and thus not fully transmitted to moving the electrons. This loss of energy can be explained with the corrugated surface and ball bearing example. Because the fields generated were much too weak for the amount of electrons, the system



**Figure 1**  
Electrons on shallow and deep “corrugated surfaces”<sup>1</sup>

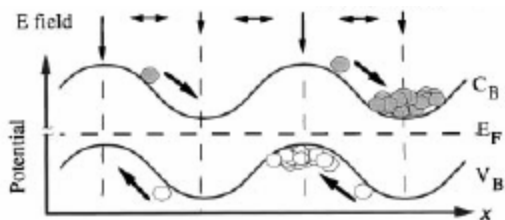
was like a corrugated surface with a trough depth much smaller than the depth of the layer of ball bearings on top of it. Because the troughs were so shallow, the surface is able to push just a few bearings along due to resistance by the higher bearings [Fig. 1]. Even when intensity of the acoustic wave was increased dramatically, the electric field waves were not big enough, and the electrons were able to move from one trough to the next due to their thermal kinetic energy.<sup>2</sup>

In 1997, a team of physicists, led by Achim Wixforth at the University of Munich, developed a new method to contain and move the electrons in ACT more effectively. The team placed a layer of indium gallium arsenide (InGaAs), a semiconductor, on top of a layer of lithium niobate (LiNbO<sub>3</sub>), a highly piezoelectric material. As a SAW was passed through the two materials, the LiNbO<sub>3</sub> produced a much stronger electric field wave than the InGaAs did alone. The field was strong enough that the electrons were split up into “quantum wires,” strips of electrons aligned in the troughs of the electric field wave.<sup>3</sup> The wires are termed as quantum because they are able to exist in various energy subbands of the semiconductor crystal. These wires were moved along by the wave much more efficiently than the electrons had previously

been moved, with the loss of power at a fortieth of what it had been before the addition of the  $\text{LiNbO}_3$ .<sup>1</sup>

Two years later, the same team passed two SAWs, with their momentum at right angles, through a quantum well similar to that used in their aforementioned experiment. As the waves passed through the semiconductor, they organized the electrons into quantum dots, quasi-zero dimensional points of electrons. These dots were quantized also, as the wires were.<sup>4</sup>

Excitons are electron-hole pairs generated when an electron is ejected from a crystal. A hole is essentially an electron with a positive charge, and can represent a positron or anti-electron. When a high-power laser is shot at a semiconductor such as InGaAs, an electron-hole pair can be produced. When such a laser is shot at an ACT system, an interesting effect occurs. Excitons are produced, and due to the difference in the charges, the electron and hole are



**Figure 2**  
Dark dots are electrons, light dots are holes.<sup>7</sup>

separated in the electric field wave; the hole locating itself at the peak of the wave compared to the electron-trough [Fig. 2]. Normally, when an electron-hole pair is produced, it will recombine, annihilate itself, and emit two photons, all within a few nanoseconds of its creation. Due to the separation caused by the wave,

however, the pair is able to exist for tens of microseconds, about 1000 times longer than previously realized. When the electrons and holes reach the end of the quantum well area, they can be allowed to recombine and produce photons if the amplitude of the electric field wave is lowered. This is accomplished by depositing a metal film on the surface of the semiconductor, which absorbs and dampens the wave. This process allows for a light signal to be transmitted across a circuit without the use of photodiodes or the like.<sup>5,6</sup>

With development and refinement, ACT has potential uses in analog electronics, charge-coupled device (CCD) replacement, and optoelectronics. In analog electronics, a need to delay a signal is often present. To create such a delay can be difficult and inefficient using ordinary electronics. Using an ACT system has been suggested and employed as a better alternative to traditional methods. A transducer is used to set up the SAW. An injection gate then deposits the electrons from the circuit onto the semiconductor, and they are carried at the speed of sound, instead of at the much faster speed of electrical current. They traverse the quantum well and are picked up by a detection gate at the other end. SAW systems, which only send and detect a SAW, have been used to delay signals, but ACT systems provide a much better alternative since the delayed signal can be modulated by regulating the flow of electrons through the injection gate.<sup>2,3</sup> Such delays are useful in applications such as electronic warfare and radar.<sup>2</sup>

Another suggested use of ACT is in replacing CCD systems. Such systems are largely used in consumer cameras, both video and digital still-shot, as well as more sensitive systems such as high-powered telescopes. The purpose of the CCD is to transport a signal from a sensor, such a photodiode, to a receptor that conveys the information to a central processor. The devices rely on complex circuits to time the transport and detection of the signals from the hundreds of sensors in a regular camera. An ACT system could be used as a replacement for the CCD in such a setup, and it has various advantages over a CCD. The sensors could be distributed across the semiconductor surface with quantum wells, and transmitted via ACT to a receptor. Not only would the ACT system transport the electrons forming the signals more efficiently, it would be self-timing due to its reliance on a wave.<sup>2</sup>

Wixforth, *et al.* suggested two primary uses of ACT in optoelectronics.<sup>6,7</sup> One use is in the delaying of optical signals. Just as in regular electronics, it is sometimes desirable to delay a

signal. Traditional methods of delaying light signals rely on long fiber-optic cables or pairs of mirrors. However, because light travels at the speed of light, a delay of 1- $\mu$ s requires such a detour to be 300-m long. Wixforth, *et al.* suggested the use of an ACT device as an optical delay, using the exciton concept. The speed of a sound wave through the semiconductor is five orders of magnitude lower than that of light<sup>6</sup> and thus such a delay device could be much smaller than that required by a purely optic delay. A second use of ACT and excitons in optoelectronics is for storage of optically encoded data. This is accomplished in much the same way as the delay functions. One problem with it, however, is that the recovered data is not in the same spot as where it was deposited, so some sort of external timing device would be necessary.

In all, acoustic charge transport is an important and applicable new field of study in physics. It has aided in the investigation of semiconductor properties, electron conveyance, and exciton properties. It also has many valid uses in useful devices, both in new inventions and applications and upgrading of other devices. It would be beneficial to both industries and consumers for research in the properties and applications of acoustic charge transport to continue.

## Endnotes and Bibliography

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<sup>1</sup> <http://focus.aps.org/v3/st14.html> (1999).

<sup>2</sup> Robert L. Miller, Carl E. Nothnick, Dana S. Bailey, Acoustic Charge Transport: Device Technology and Applications, Artech House, Massachusetts, 1992.

<sup>3</sup> M. Rotter, A. V. Kalameitsev, A. O. Govorov, *et al.*, “Charge Conveyance and Nonlinear Acoustoelectric Phenomena for Intense Surface Acoustic Waves on a Semiconductor Quantum Well,” *Phys. Rev. Lett.*, **82**, 2171 (1999).

<sup>4</sup> M. Rotter, A. V. Kalameitsev, A. O. Govorov, *et al.*, “Self-Induced Acoustic Transparency in Semiconductor Quantum Films,” *Phys. Rev. Lett.*, **87** (2001).

<sup>5</sup> <http://www.aip.org/enews/physnews/1997/split/pnu321-1.htm> (1997).

<sup>6</sup> C. Rocke, S. Zimmermann, A. Wixforth, *et al.*, “Acoustically Driven Storage of Light in a Quantum Well,” *Phys. Rev. Lett.*, **78**, 4099 (1997).

<sup>7</sup> S. Zimmermann, A. Wixforth, J. P. Kotthaus, *et al.*, “A Semiconductor-Based Photonic Memory Cell,” *Science*, **283**, 1292 (1999).