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PHOTOINJECTOR IMPROVEMENT AND CONTROL BY SURFACE ACOUSTIC WAVES*

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Abstract

A new technique is being developed to enhance the efficiency of photocathodes used for electron sources in order to improve emission capabilities of electron sources, such as bunch charge and average current. The proposed technique is based on the use of surface acoustical waves (SAW) generated on the piezoelectric surface of a GaAs photocathode. The generation of SAW on piezoelectric substrates is known to produce strong piezoelectric fields that propagate on the surface of the material. These fields can significantly suppress recombination effects and result in enhanced quantum efficiency of photoemission. Experimental measurements of photoemission quantum efficiency are planned on semiconductors used as photocathode materials (e.g., GaAs) in presence of SAW with varied parameters. The experimental results will be used as input for physics modeling that will provide a basis for the design of operational SAW-enhanced photocathodes. The improved quantum efficiency and parameter control expected from the use of SAW will be useful for electron sources in particle accelerators as well as for commercialization in other fields, such as electron microscopy.

MOTIVATION

An experiment [1] reported strikingly long lifetimes of photo-excited electrons in a GaAs sample in the presence of piezoelectric fields induced by SAW. In this experiment, electrons and holes were photo-generated by a 5 μm diameter laser spot and were transported towards a semi-transparent metal strip, at which electron–hole recombination was induced by screening out SAW. The key observation relevant for potential applications for polarized electron sources is that spin polarization of the electrons during transport was preserved, at a distance of hundreds of microns. An observed increase of electron diffusion length with minimized de-polarization effects is an important motivation for our study. The advantages provided by the use of piezoelectric fields are not only limited to applications of SAW. Realization of piezoelectric fields in nano-scale devices has recently led to the development of the entire field of *piezotronics* and *piezophototronics* [2] that results from three-way coupling of piezoelectricity, photonic excitation, and semiconductor transport, leading to enhanced performance of photovoltaic cells and photon detectors.

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It is our main objective to demonstrate the effects of piezoelectric fields, via SAW application, on photocathode performance. To the best of our knowledge, such an effect was never demonstrated before.

GENERATION OF SAW

SAW are presently a basis of a well-established technology used in multiple applications, primarily in SAW devices associated with electronic circuits. The telecommunications industry is probably the largest consumer of SAW devices, with an estimated 3 billion acoustic wave filters used per year [3]. In most applications SAW are generated (and detected) using a piezoelectric effect, namely, conversion of electrical energy into mechanical energy and vice versa. This is accomplished through the use of Interdigital Transducers (IDT) placed on a piezoelectric substrate, as shown in Fig. 1. An AC voltage, typically with frequencies up to 1 GHz, is applied to the IDT, resulting in one or more SAW propagating with the speed of sound v_{SAW}. The spacing λ of the structure on the IDT defines the wave number of each of the SAW, $k=2\pi/\lambda$. SAW are deformations of the crystal lattice that produce a periodic modulation of the electric charge and potential in piezoelectric semiconductors, such as GaAs (Fig.1).

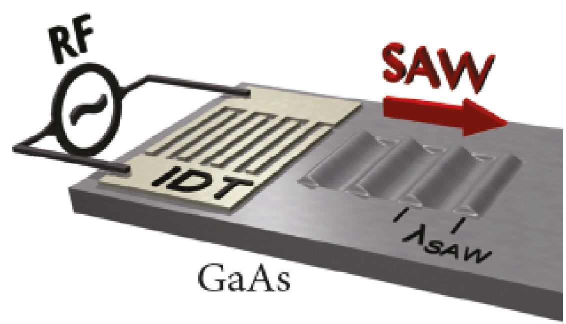

Figure 1: Generation of SAW on a piezoelectric substrate with an interdigital transducer (IDT) powered by an RF-source.

Typical values of the parameters related to experiments of interest [1,4] are frequency f = 840 MHz, wavelength λ_{saw} = 3.4 μm, and speed $v_{SAW} \approx 3$ km/s. More formally, SAW are acoustic phonons with a linear dispersion relation between energy and wave vector, and their eigenmodes are described by the theory of elasticity. For a homogeneous medium, the three bulk elastic

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eigenmodes for a wave vector are obtained from solutions of the elastic wave equation for the acoustic displacement field, see, for example [5].

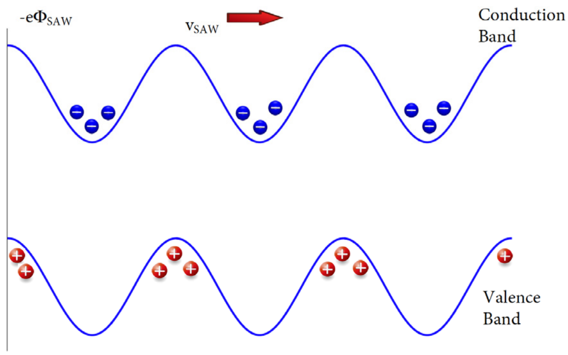

Figure 2: Band distortion, dynamical formation of type-II band structure in GaAs and charge carrier separation under piezoelectric potential Φ_{SAW} of propagating SAW.

The piezoelectric field can be defined as a gradient of the piezoelectric potential (Φ_{SAW}). Importantly for us, previous experimental measurements demonstrated acoustically-driven charge separation in piezoelectric materials due to a potential Φ_{SAW} of the type shown in Fig. 2. We obtained the potential of Fig. 2 using standard methods for solving the Poisson equation.

ELECTRON-HOLE RECOMBINATION

Key findings in the physics of SAW in connection to lifetimes of photogenerated carriers were made by Rocke and collaborators [4], who observed that strong piezoelectric fields accompanying SAW on a semiconductor quantum well structure lead to efficient trapping of the photogenerated electron-hole pairs in the moving lateral potential superlattice of the sound wave. The resulting spatial separation of electrons and holes in the traveling SAW reduced their recombination rate by several orders of magnitude. Observed quenching of photoluminescence (PL) from [1,4] demonstrated almost complete suppression of electron-hole recombination for higher acoustic-wave powers. The same publications reported that electron-hole pairs can be efficiently transported by SAW over millimeter-scale distances. This field remains active, with further applications of SAW in acoustic charge transport in GaAs nanowires.

In the experiment, electrons and holes were transported by SAW over relatively large distances of hundreds of microns. It exceeds by several orders of magnitude the diffusion length of electrons in the same material. This experimental fact is the main motivation for the present project: SAW provides a possibility to extend the diffusion length of photoexcited electrons in photocathodes with a major impact on photoemission efficiency, as follows from Spicer's three-step model for photoemission.

EFFECT ON QUANTUM EFFICIENCY OF PHOTOEMISSION

Possible implications of SAW for photocathode-based electron sources used for electron accelerators were pointed out in [6]. A comprehensive review of photocathode technologies for applications in energy-recovery linacs may be found in [7]. An important limitation is that in conventional superlattice photocathodes, the short radiative lifetime of electrons (n) and holes (p) limits the quantum efficiency (QE) of photoinjectors. For example, the present QE of photocathodes is typically limited to the level of a few per cent or so (the ratio of electrons generated to the number of incident photons).

To evaluate quantum efficiency in the presence of SAW, we use three-step photoemission model of Spicer [8]. We follow Spicer's approach that considers the process of photoemission in three steps: (a) Absorption of a photon; (b) Transport to the surface and (c) Escape over the potential barrier. Assuming that the (uniform) material under irradiation is an infinite half-space with a surface at x=0, the quantum efficiency (QE) of a photocathode is given by the formula

$$QE = (1-R)\frac{\alpha_{PE}}{\alpha}\frac{P_E}{1+\frac{l_\alpha}{L}}$$

where R is light reflectivity, α_{PE} is the absorption coefficient for electrons excited above the vacuum level, α is the absorption coefficient of a semiconductor, PE is the probability to escape of electrons reaching the surface, $l_a=1/\alpha$ is the photon absorption length and L is the electron diffusion length.

Introducing SAW in a semiconductor, with accompanying piezoelectric fields, will result in the following change in the parameters in the formula above for QE:

- Increase of absorption leading to free carriers α_{PE}, since near-bandgap photon absorption via exciton mechanism leads to creation of additional electrons after their ionization in SAW;

- Increase in electron diffusion length L. This effect indeed takes place, as shown in experiments [1,4], where lifetimes of electrons carried by SAW can be extended by several orders of magnitude. Even if only a small percentage of free carriers extend their lifetime (against recombination) by a significant amount, it may result in a substantial increase of the diffusion length, since $L = \sqrt{D\tau}$, with D being a diffusion constant. This effect can be understood in terms of the density of free charge carriers. No matter what electron-hole recombination mechanism is dominant for a given case, the recombination rate is proportional to the product of electron (n) and hole (p) concentration. Reducing spatial overlap of electrons and holes leads to reduced recombination rates and increased lifetimes of electrons, which improves their chances to be emitted into vacuum after a sequence of electron-phonon scattering events.

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Unfortunately, we do not have sufficient data on dynamics of recombination through recombination centers or traps; there is experimental evidence, however, that diffusion length also increases (by a factor of two, subject to a choice of parameters) in this case [9]. Another important factor that requires experimental clarification is dependence of the recombination rate on acoustic power and a possible role of acoustically vibrating charged defects that result in fluctuations of electromagnetic field strength that is hard to predict theoretically [9]. These observations warrant further experimental investigations using common photocathode materials, while the piezoelectric properties of GaAs commonly used in photocathodes make it a material of choice for SAW studies.

PLACEMENT OF SAW DEVICES ON THE PHOTOCATHODE

In the course of this project we also gained insight into manufacturing and operational problems for SAW devices to be used with existing photoinjectors. Namely, can an IDT be reliably attached to a photoinjector surface? Will it sustain thermal damage during heat processing of the photocathode? We were able to address some of these questions during the first phase of this project. An IDT device was designed and placed on a surface of standard GaAs photocathode wafers that are used for a polarized electron source at Jefferson Lab accelerator (CEBAF). Furthermore, the IDT device was subjected to heat processing at ~ 550C [10]. The results of the test were encouraging: visual inspection showed that IDT was not damaged during heat processing, see Fig. 3.

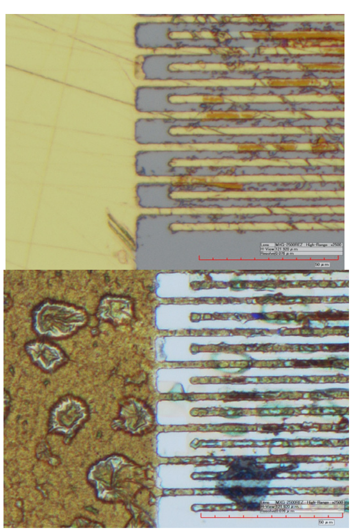

Figure 3: IDT device on GaAs substrate before (upper picture) and after (lower picture) heat processing at about 550C [10].

IDT FABRICATION

In order to begin preliminary investigations of Surface Acoustic Wave (SAW) devices, our team initiated a project to design, fabricate and test several devices. The primary material for this initial test was GaAs due to its use in photocathodes for electron accelerators. In addition, several test structures were designed and fabricated for $LiTaO_3$ and $LiNbO_3$ material systems due to the GWU team's prior experience and background with such systems. The SAW devices designed/fabricated have four different wavelengths (defined by periodicity of IDT): 8, 12, 16 and 20 μm. To prevent short circuits in the IDT during operation in doped GaAs, we placed the IDT on an insulating anodized layer deposited on photocathode surface, while leaving an area adjacent to the IDT without this insulating layer in order to enable photoemission. IDTs were also placed on samples of intrinsic GaAs for further QE measurements.

SUMMARY

Existing experimental data demonstrated that SAW propagating on piezoelectric substrates generates fields as high as 1 MV/m.

Based on the observed effects of SAW on photoemission, we proposed and studied methods to enhance the performance of photocathodes using SAW. If successful, the developed technique will help to increase efficiency of electron sources used in electron accelerators and electron microscopy.

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