RAISING PHOTOEMISSION EFFICIENCY WITH SURFACE ACOUSTIC WAVES*

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Abstract

We are developing of a novel technique that may help to increase efficiency of photocathodes, so lower-power lasers with a smaller beam spot can generate more intense electron beams having smaller emittances. The technique is based on the use of Surface Acoustic Waves (SAW) in piezoelectric materials, such as GaAs, that is commonly used in photocathodes. Piezoelectric fields produced by the travelling SAW spatially separate electrons and holes, reducing probability of their recombination and resulting in enhancement of quantum efficiency of photoemission, while preserving high degree of spin polarization.

MOTIVATION

We were motivated by an experiment [1] that reported strikingly long lifetimes of photoexcited electrons in GaAs sample in presence of SAW.

In their experiment, electrons and holes were photogenerated by a 5 μm diameter laser spot and are transported towards a semi-transparent metal strip, at which electron–hole recombination is induced by screening out SAW. The key observation relevant for potential applications in polarized electron sources is that spin polarization of the electrons during transport is preserved, at a distance of hundreds of micron. This effect can be used for polarized electron sources, since high currents of polarized electrons are required by a number of fundamental physics experiments involving electron scattering. An observed increase of electron diffusion length with minimized de-polarization effects is an important motivation for this study.

INTRODUCTION TO SAW

SAW were known from the 19th century as Raleigh waves; they are described as a surface mode of sound propagation in materials. 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 [2]. 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 Inter-Digital Transducers (IDT) placed on a piezoelectric substrate [2]. An AC voltage, typically with frequencies up to 1 GHz, is applied to the IDT, resulting in one or more SAW

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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.
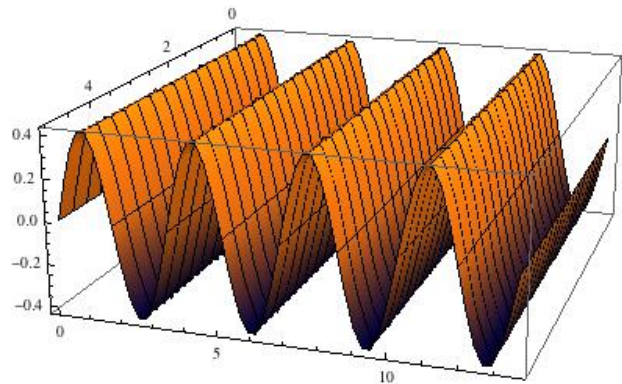

Figure 1: Piezoelectric potential Φ_{SAW} in a harmonic approximation in GaAs substrate calculated for experimental conditions of [3]. Units are Volts (vertical axis) and μm (horizontal axes). In this figure, SAW propagates from left to right, the surface of the GaAs substrate is in XY-plane. This potential corresponds to a lateral piezoelectric field with an amplitude of 0.8 MV/m and SAW wavelength $\lambda_{SAW} = 3.4$ μm.

Typical values of the parameters related to experiments of interest [3] are frequency f = 840 MHz, wavelength λ = 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 eigenmodes for a wave vector are obtained from solutions of the elastic wave equation for the acoustic displacement field, see, for example [4]. 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 Figure 1. We obtained the potential of Figure 1 using standard methods for solving Poisson equation.

EFFECTS OF SAW ON PHOTOEMISSION

Key findings in the physics of SAW in connection to photoemission were made by Rocke and collaborators [3], who observed that strong piezoelectric fields accompanying SAW on a semiconductor quantum well

structure lead to dissociation of optically generated excitons and efficient trapping of the created 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 [3] demonstrated almost complete suppression of electron-hole recombination for higher acoustic-wave powers. The same publication reported that electron-hole pairs can be efficiently transported by SAW over millimeter-scale distances.

These results are interpreted as follows [5]. The excitons confined in an InGaAs quantum well are affected by a moving piezoelectric potential of a surface acoustic wave (SAW) generated in the GaAs substrate of the sample structure and propagating along the plane of the quantum well. Within the piezoelectric field of the wave that can be as strong as 1MV/m, the excitons polarize and finally dissociate into electron-hole pairs at sufficiently high fields. The dissociated pairs are transferred to the potential wells associated with the traveling wave. 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 extension of diffusion length of photoexcited electrons in the photocathodes with a major impact on photoemission efficiency, as follows from Spicer's three-step model for photoemission.

SAW FOR PHOTOINJECTORS

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 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 $x=0$, quantum efficiency (QE) of a photocathode is given by the formula

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

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 a 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 semiconductor, with accompanying piezoelectric fields, will result in the following change in the parameters for the above formula 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 [3], 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 L. 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.

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 [5]. These observations warrant further experimental investigations using common photocathode materials.

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 IDT be reliably attached to 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. The results of the test were encouraging: visual inspection showed that IDT was not damaged during heat processing, see Figure 2.
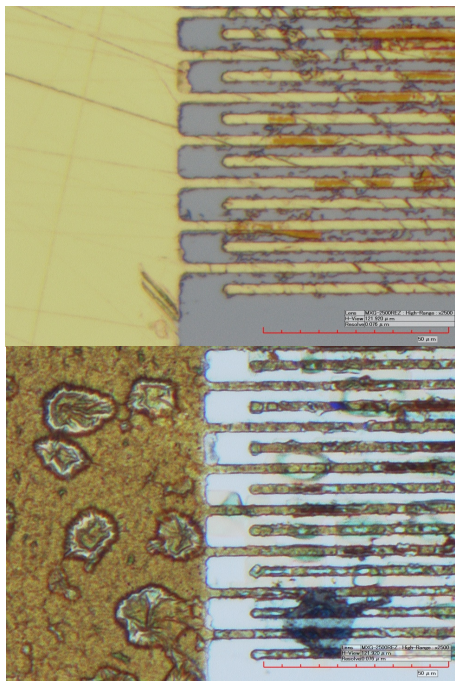

Figure 2: IDT device on GaAs substrate developed in collaboration with GWU before (upper picture) and after (lower picture) heat processing at ~ 550C.

IDT FABRICATION

In order to begin preliminary investigations of Surface Acoustic Wave (SAW) devices, our team in collaboration with the George Washington University (GWU) initiated a project to design, fabricate and test several devices. The primary material system to perform this initial test was GaAs due to their use by and the experience of the Jefferson Laboratory in photocathodes. In addition, several test structures were designed and fabricated for the 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 IDT without

this insulating layer in order to enable photoemission. IDT 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 one 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.

ACKNOWLEDGEMENTS

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