RAISING PHOTOEMISSION EFFICIENCY WITH SURFACE ACOUSTIC WAVES*

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Abstract

Current and future synchrotron radiation light sources and free electron laser facilities are in need of improvements in Electron Gun Technology, especially regarding the cost and efficiency of photoinjectors. The generation of Surface Acoustic Waves (SAW) on piezoelectric substrates is known to produce strong piezoelectric fields that propagate on the surface of the material. These fields significantly reduce the recombination probability of electrons and holes which can result in enhanced quantum efficiency of photoemission. Additional advantages are provided by the mobility of charge carriers that can be controlled by SAW. It is expected that this novel feature will result in enhanced efficiency of photocathode operation, leading to the production of intense, low emittance electron bunches at a high repetition rate using laser excitation.

INTRODUCTION

SAW were known from the 19th century as Raleigh waves; they are described as a surface mode of sound propagation in materials [1]. 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].

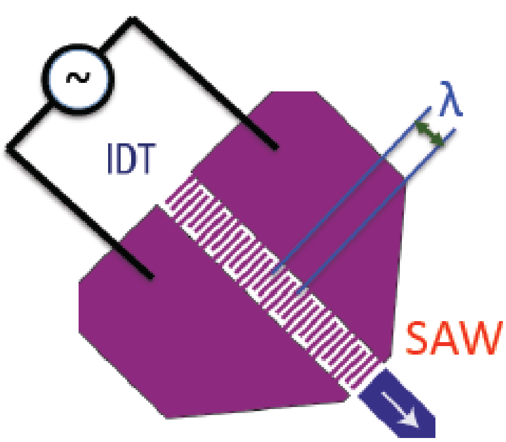

Figure 1: Schematic layout of SAW generation.

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, as shown schematically in Figure 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. 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 ($\vec{u}$) that can be written as [4]:

$$\vec{\nabla}\cdot\boldsymbol{\sigma} = \rho\frac{\partial^2\vec{u}}{\partial t^2}$$

This equation is solved using the following constitutive relations

$$\boldsymbol{\sigma} = \boldsymbol{c}\varepsilon - \mathbf{e}\vec{F},$$
$$\vec{D} = \chi\vec{F} + \boldsymbol{e}\varepsilon$$

In the above formulas, $\boldsymbol{\sigma}$ and ε are the stress and the strain tensors, while $\vec{F}$ and $\vec{D}$ denote, respectively, piezoelectric and electrical displacement fields. The piezoelectric field can be defined as a gradient of the piezoelectric potential (Φ_{SAW}) as $\vec{F} = -\vec{\nabla}\Phi_{SAW}$. The material parameters involved in the above equations are the density ρ, the elastic stiffness tensor **c**, the piezoelectric tensor **e** and the static dielectric tensor χ. Surface elastic modes correspond to solutions of the elastic wave equations that are localized within the range λ near the surface and simultaneously satisfy boundary conditions following from continuity of electrical and strain fields.

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-

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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] is presented in Figure 2 which 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. An opposite effect was found [3] for the standing SAW, which results in induced radiative recombination of electrons and holes under interference of two counter-propagating SAW, as shown in Figure 3. It is therefore possible to either increase or decrease radiative lifetimes of electron-hole pairs using different configurations of SAW. In addition, as shown in [5], dynamically trapped electrons and holes can be transported by SAW over macroscopic distances, while preserving the spin polarization of the electrons. The implications of SAW for the development of highly efficient photovoltaic materials were recently discussed in [6].

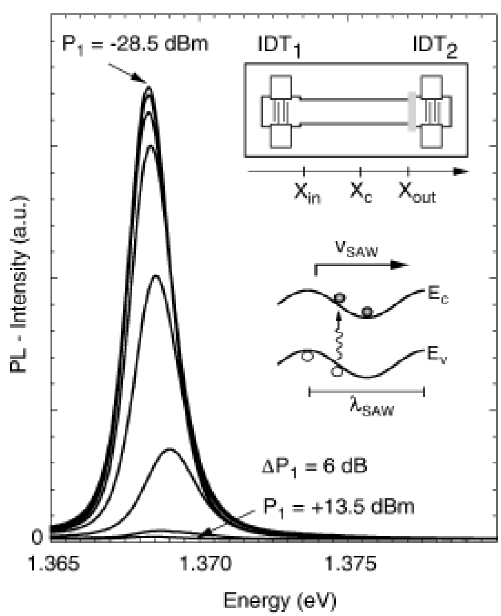

Figure 2: Photoluminescence spectra of a single 10 nm wide InGaAs/GaAs quantum well structure for different acoustic powers. The optical excitation occurs at the site $x = x_c$ with an intensity of 10 mW/cm^2 and laser wavelength = 780 nm. The inset schematically depicts the sample design with two interdigital transducers (IDT) and the storage of optically generated excitons in the potential of a surface acoustic wave.

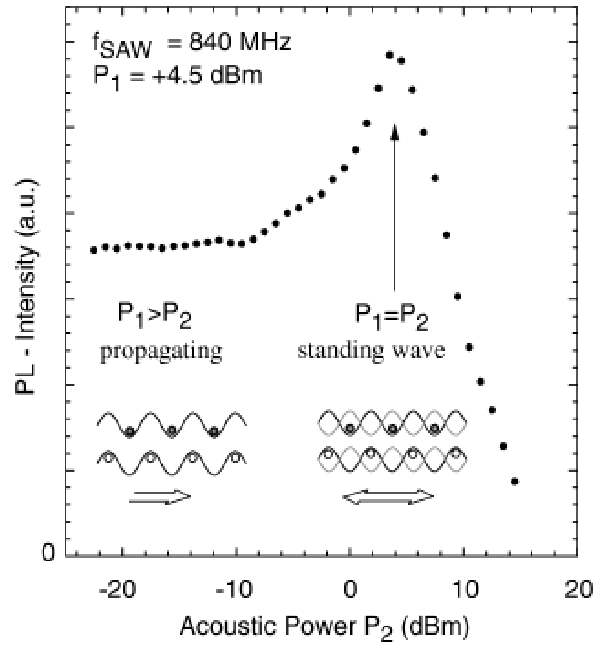

Figure 3: Photoluminscence is enhanced for standing SAW compared to propagating SAW.

SAW FOR PHOTOINJECTORS

Consider implications of SAW on photocathode-based electron sources used for electron accelerators. 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 (*e*) and holes (*h*) 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).

Published experimental results on SAW imply that in the state-of-the art GaAs photoinjectors with negative-affinity coating, extending electron lifetime with SAW will result in extended time spent by electrons in the conduction band, leading to increased photoemission efficiency. Also, SAW would result in creation of additional carriers (electrons) due to the experimentally observed effect of exciton ionization by piezoelectric fields [3]. Enhancement in photoemission efficiency in GaAs semiconductors due to propagating SAW was observed experimentally, albeit for low-intensity photon fluxes, and reported in [8,9] in application to development of sensitive photodetectors. Measurements of absorption [8] have shown that SAW-stimulated materials may reach rather high photocurrent efficiency, and that up to 85% of incident photons lead to creation of electron-hole pairs in the GaAs channel.

One more possibility of QE enhancement of photocathodes is based on an observation that SAW-generated electromagnetic waves in piezoelectric substrates on metal surfaces [10] resulted in changes of the work function due to the spatial lattice displacement.

We consider separately standing SAW (as opposed to travelling SAW) and its effect on photocathode efficiency. Since for a standing wave spatial separation of electrons and holes is not maintained, but it varies in time with SAW frequency, the effect of SAW on radiative lifetime may be opposite. Namely, standing SAW may favor recombination of electron and holes, thereby shortening their radiative lifetime, as illustrated in Figure 3. In specific cases of surface-charge saturation under a high-intensity photon flux [11], quantum efficiency of the photocathode benefits from shorter radiative lifetimes of e-h pairs. In order to reduce surface photovoltage effects, higher recombination rates were previously achieved by higher surface doping concentrations [12]. We conclude that the standing SAW may reduce the surface photovoltage under the conditions of charge saturation, thereby providing an important alternative to doping. Other possibilities for reduction of photovoltage effects include controlled removal of holes due to enhanced mobility of charge carriers provided by SAW.

SUMMARY

Existing experimental data demonstrated that SAW propagating on piezoelectric substrates generates fields as high as one MV/m. These fields result in the following effects that may contribute to enhanced quantum efficiency of the photocathode.

- Ionization of optically-generated excitons resulting in creation of additional electron-hole pairs.
- Extension of the lifetime of electron-hole pairs against radiative recombination.
- Possible reduction of surface charge effects with SAW.

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

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