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SURFACE ACOUSTIC WAVE ENHANCEMENT OF PHOTOCATHODES*

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Abstract

Numerical simulations and fabrication techniques are being used to investigate the use of surface acoustic waves to suppress electron-hole recombination on the surface of GaAs photocathodes in order to increase the quantum efficiency for polarized and unpolarized electron beam generation.

INTRODUCTION

We are studying the effect of surface acoustic waves (SAWs) on photocathodes used in electron sources for electron accelerators, photon detectors and electron microscopes. It is expected that this novel feature will result in enhanced efficiency of photocathode operation, leading to production of intense, low emittance electron bunches feasible at high repetition rates up to CW with existing laser excitation technology thanks to the low demands on the required laser power, wavelength and therefore optics. Tasks to be performed in Phase II of the project will involve both experimental measurements and more advanced computer simulations.

SAWs (Fig. 1) 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].

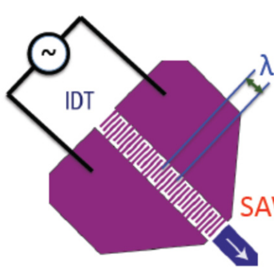

Figure 1: Schematic layout of SAW generation.

In most applications SAWs 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 2. An AC voltage, typically with frequencies up to 1 GHz, is applied to the IDT, resulting in the SAW propagating with the speed of sound. The spacing λ of the structure on the IDT defines the wave number of the SAW, $k=2\pi/\lambda$. SAWs 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 vsaw ≈3 km/s.

Previously we have presented the theoretical description of the use of SAWs to control and enhance the QE of photocathodes at conferences [4,5,6,7]. Further developed modelling and preliminary engineering solutions shown below provide a path for future device fabrication. The modeling with COMSOL Multiphysics simulation suite done by Prof. Zaghloul's graduate student Mr. Dong, who was supported by a grant from MuPlus, Inc., demonstrates the predicted effects. He also came up with a solution to a problem that was not earlier appreciated. Namely the piezoelectric coupling between the IDTs to the GaAs photocathode surface is too weak. An important innovation to the practical realization of SAW photocathode devices consists in adding additional layers of materials between the IDTs and the photocathode.

SIMULATION

For the Phase I proposal, we used COMSOL Multiphysics as a simulation tool to build models of SAWs propagating on p-type GaAs substrate. It was used to calculate and simulate the SAW-induced periodical potentials, energy bands bending effects, as well as the spatial separation and transportation characteristics of carriers inside semiconductor. Then light illumination was applied to the surface of p-type GaAs layer in simulations and a photo-generation rate was set up to create electron-hole pairs. Simulation results proved that recombination rates in p-type GaAs can be significantly suppressed by over an order of magnitude under the effect of SAWs, and result in more electrons to be transported and used for emission, and thus has good potential to improve the performance of photocathode devices.

Under the DOE STTR Phase I grant, we have continued by modifying and optimizing our simulation structure and models in order to get more practical and better outcomes. We simulated a ZnO layer on top of p-type GaAs, which is identical to the ones fabricated that are described below. Also the light illumination has been modified to be a laser beam, which has same parameters as real ones commonly used in photocathode applications.

In addition to electron concentrations on the surface, we also calculate the ratio of photo-generated electrons per photon absorbed, which leads to next-step calculation of quantum efficiency. Also, the dependence of enhancement on both SAW intensity and SAW wavelength are modeled and simulated, which gives us more knowledge to optimize the structure of our SAWs devices.

Figure 2 shows the cross-section view of the simulation structure. The substrate is highly p-doped GaAs. A thin

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ZnO layer is deposited on the GaAs because of its strong piezoelectric effect, which can be used to enhance the generation of surface acoustic waves. On top of the ZnO layer on both sides, two pairs of interdigital transducers (IDTs) made of aluminum are deposited and used as metal contacts. Among them, IDTs no.1 and no.3 are grounded. IDTs no.2 and no.4 are applied to AC input voltage, which is expressed in the equation below:

$$V\_in = V_0 \times \sin(2\pi \times f_0 \times t), \quad (1)$$

where V_0 is chosen as 1 volt, and f_0 is set up to 433 MHz during simulation.

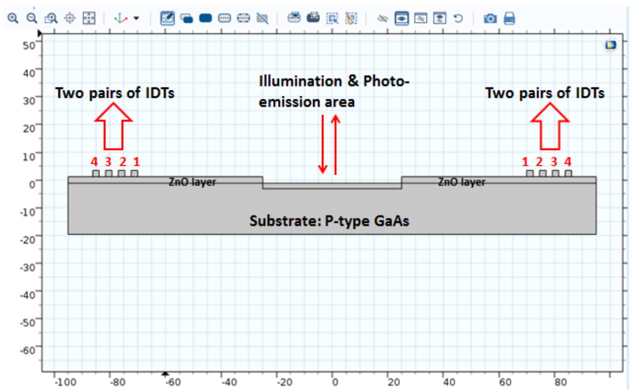


Figure 2: Simulation structure (unit: um).

In addition, surface acoustic waves are treated as Rayleigh Waves in this simulation, and the wave velocity is set to 3996 m/s. Then the wavelength can be calculated to be 9.2 um. Regarding to the dimensions, the thickness of the substrate is 18.5 um and its width is 190 um. IDTs are all 2.3 um * 2.3 um, and the distance between each IDT is also 2.3 um.

In simulation, light illumination is applied to the center of the GaAs substrate, as indicated in Figure 2. The width of that area is 50 um and the depth is 2 um. Photo-generated electrons are created in simulation under illumination of a laser beam. The power of laser is set to 5 W/mm^2. The wavelength of photons is set to 825 nm, which gives the photon energy equal to 1.50 eV.

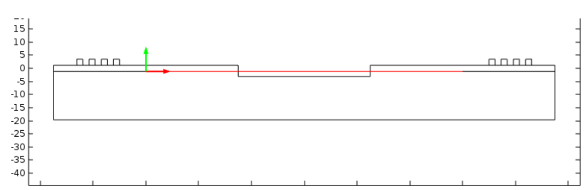
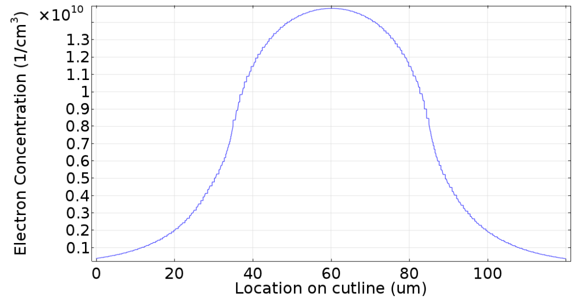
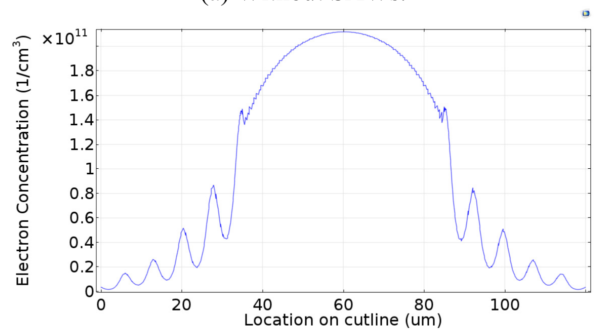


Figure 3: Cutline (red) used to extract results.

The red line with arrow shown in Figure 3 indicates the location where simulation results are extracted to plot curves. Results are extracted on the top surface of the GaAs layer in the horizontal direction, which is also the propagation direction of SAWs. Figure 4 plots the electron concentrations on the top surface of the photo-emission area on the GaAs layer. Comparing (a) without SAWs and (b) with SAWs, shows that about 14 times more electrons are generated under the effect of surface acoustic waves.



(a) Without SAWs.



(b) With SAWs.

Figure 4: Electron concentrations extracted on cutline.

In order to verify the dependence of the enhancement on SAW intensity, the amplitude of the applied AC voltage is swept from 0.2 V to 2.0 V at a step of 0.1 V. Simulation results are shown in Figure 4.

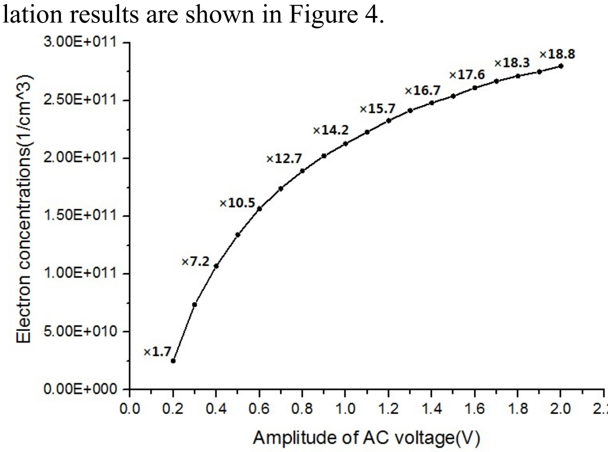


Figure 5: Dependence on amplitude of AC voltage.

In Figure 5, the y-axis shows electron concentrations on the top surface of GaAs after applying SAWs generated by different amplitudes of AC voltage. The numbers indicated above dots on the line refer to enhancement of surface electron concentrations due to SAWs.

FABRICATION AND MEASUREMENT

Two SAWs devices with different IDT width (0.9 um / 2.3 um) were fabricated and measured. Photos from an optical microscope show the outcome of fabrication and the accuracy of IDT sizes for the 0.9 um device. Finally, I-V curves are plotted using measurement data extracted from the semiconductor device analyzer.

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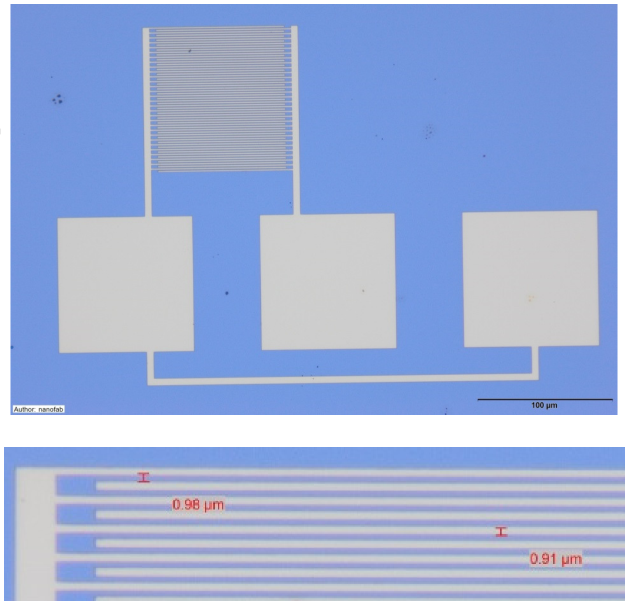

Figure 6: Structure of metal IDTs (0.9um).

Figure 6 shows the finger electrode IDTs that are 0.9 um×100 um each. The three square pads are contact pads that used to connect to the probe station. The pictures are taken from an optical microscope. The arrows and numbers in red in the second picture show the width of IDTs and distance between each IDT. Those are the sizes we designed, and proves the accuracy of the fabrication process. Photos taken from the network analyzer present both transmission and reflection characteristics of the SAW devices.

In Figure 7, the black line is same as the one shown in Figure 7. It is the I-V curve of a SAW device with 2.3 um IDTs on p-type GaAs. Then another same SAWs structure with 2.3 um IDTs are fabricated on ZnO layer, and measured. The I-V curve is shown in Figure 8 as the red line. From the comparison, we can see the voltage limit increased from 2 volts to 6 volts. This is because ZnO has larger energy bandgap than GaAs, and thus it is able to resist higher voltage and more difficult to breakdown.

SUMMARY

In previous attempts to place IDTs on GaAs wafers, we did not succeed to find one supplier who could provide even one working example. Under this Phase I grant, by virtue of having an excellent GWU team with experience, simulation tools, and a new facility, we now have a factory to make new variants of SAW designs in a few days with diagnostics to characterize the SAW operation almost in real time. The simulations have shown a potential improvement of GaAs photocathode QE performance by a factor of over 14. The importance of the SAW frequency on the QE has been shown by the simulations. The nanofabrication of GaAs SAW devices and their characterization is now done in a matter of days, allowing the start of a continuous improvement process. So far, the addition of a ZnO layer has been experimentally shown to produce the predicted improvement in the piezoelectric coupling, Aluminum IDTs are shown to work better than Ti/Au. SiO2 and ZnO thicknesses were explored to find the optimum for those materials as the piezoelectric enhancing intermediate layer. The SAW device was shown to survive the high temperature annealing process needed for cleaning the photocathode surface. The optical microscope, network analyzer, and SEMs were used to compare IDT structures with 900 nm and 2300 nm finger electrode sizes

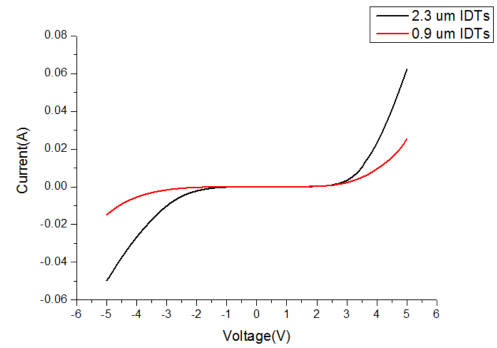

Figure 7: I-V for 2.3 um and 0.9 um IDTs SAW devices.

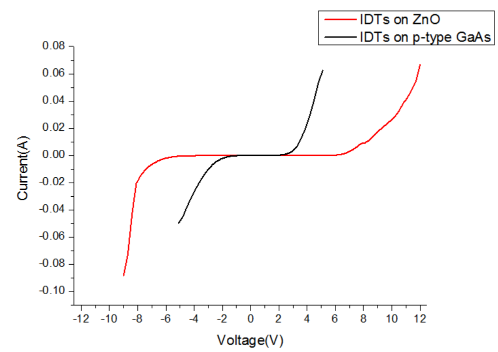

Figure 8: I-V SAWs devices with and without ZnO.

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