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Properties and Applications of a Novel Electroacoustic Interaction in GaAs Resonant Tunnelling Structures

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1. Introduction

We present experimental and theoretical work on a new electroacoustic system, which exploits the interaction between a 1 GHz surface acoustic wave (SAW) and electrons in a GaAs-AlGaAs resonant tunneling structure (RTS). Potential applications for this system in signal processing and power microwave devices are discussed, along with a suggested mechanism for a non-dispersive SAW transducer which relies on the nonlinear properties of the system.

The SAW is a mechanical wave which, when propagating on a piezoelectric surface, is accompanied by a travelling wave of electrostatic potential. Consequently, the interaction between SAWs and low-dimensional electrons in semiconductors has been the focus of much research, both for basic physics (e.g. [1,2]) and for device applications. Much of the applied research has concentrated on hybrid devices, comprised of a good piezoelectric, such as $LiNbO_3$, in close proximity to a semiconductor [3,4]. However, these devices are limited by the complexity of manufacturing and relatively low operating frequencies.

The system presented here (shown schematically in Fig. 1) surmounts these difficulties by using a monolithic design where the vertical component of the SAW field interacts with vertical currents in the GaAs structure. The structure itself consists of (from top to bottom): a doped cathode; a double-barrier quantum well; a wide depletion region to prevent screening of the SAW; and a highly doped substrate. The current-voltage characteristic of the structure is typical of RTSs, displaying strong nonlinearity including a region of negative differential resistance.

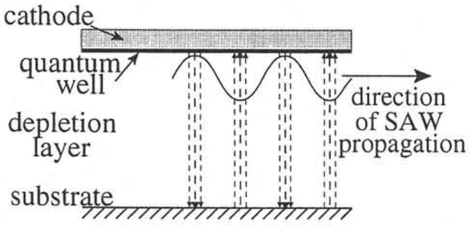

Fig. 1. Schematic diagram of layer structure of GaAs RTS, showing spatial modulation of SAW field.

The current through the structure depends only on the potential across the quantum well, rather than the potential across the entire structure. Since the well is located close to the surface, this allows the current to be spatially modulated by the SAW field. The result is a charge density wave in the depletion region, superimposed on the background spatial charge induced by the dc bias. The electric field associated with this charge density wave piezoelectrically excites a mechanical wave, providing a feedback mechanism to the SAW.

If the RTS mesa is much longer than the SAW wavelength, then the charge density wave associated with a travelling SAW will cause no alternating current in the external circuit, since the net current will be independent of time. Patterning the RTS as a grating with pitch equal to the SAW wavelength allows a microwave current to be induced in the external circuit [5]. Alternately, two counterpropagating SAW beams can be applied to create a standing SAW at the (unpatterned) RTS. Using this configuration, the second and subsequent even harmonics of the external current are non-zero if the system is nonlinear.

2. Experiment

The device design (shown in Fig. 2) consists of an RTS situated between two SAW transducers; this configuration allows the RTS to be subjected to either travelling or standing SAWs. The microwave signal through the RTS triggered by the SAW was measured as a function of the dc bias on the RTS. Measurements were taken in the linear regime (at 1 GHz), using a grating-patterned RTS; and also in the nonlinear regime (second harmonic at 2 GHz), using a simple rectangular RTS.

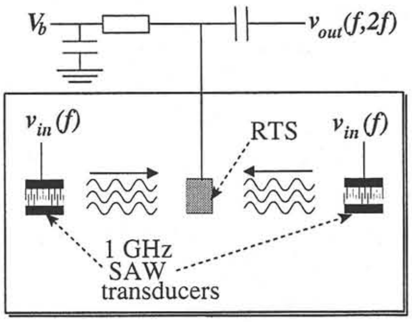

Fig. 2. Schematic diagram of device. Microwave power $v_{in}(f)$ is applied to the transducers, dc bias V_b is applied to the RTS, and a microwave signal $v_{out}(f,2f)$ is measured in the external circuit.

Typical experimental data is shown for the linear (Fig. 3) and nonlinear (Fig. 4) device configurations, along with the dc current through the RTS. Strong enhancement of the microwave signal in Fig. 3 is observed as the bias approaches the negative differential resistance regime: as expected, the linear signal follows the magnitude of the dc differential conductance of the RTS. The dashed line shows the predictions of a simple model which takes into account the spatial distribution of the SAW electric field and the nonlocality of the structure's conductivity; qualitative agreement between theory and experiment is observed.

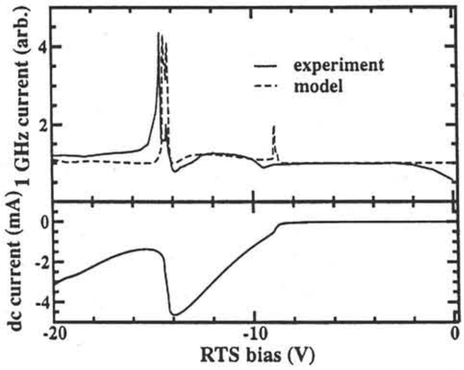

Fig. 3. Experimental and modelled data showing the microwave signal in the external circuit from an RTS patterned as a grating. Also shown is the dc I-V characteristic of the RTS.

The nonlinear signal arising from the application of a standing SAW displays strong peaks in both the positive and negative directions around the region of negative differential resistance (Fig. 4). This dependence is once again predicted by a simple phenomenological model, which is related to the derivative of the dc differential conductance of the RTS.

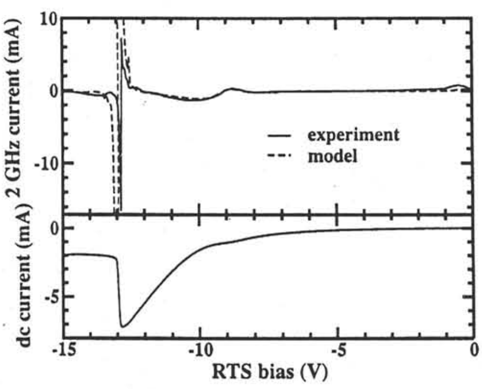

Fig. 4. Experimental and modelled data showing the second harmonic signal induced in the external circuit by a standing SAW with an unpatterned RTS. Also shown is the dc RTS current.

Devices in the nonlinear configuration were fabricated from two wafers with different cathode layer thicknesses (120 nm and 300 nm). It was initially thought that a thinner cathode layer would allow a stronger interaction, since the quantum well would be closer to the surface where the SAW propagates. However, the opposite result was observed in experiments. Calculations were performed taking into account the effect of the carriers in the highly doped cathode, which resulted in a nonmonotonic relation between the strength of the SAW field and the thickness of the cathode. These calculations agreed with our results, and should enable the thickness of the cathode layer to be optimized in future devices.

3. Discussion

Possible applications for this interaction can be envisaged in three general areas. Firstly, devices in this configuration may offer substantial improvements in signal processing applications such as real time signal convolution, compared to existing SAW-based devices. The main advantage of this design is simplicity of manufacturing relative to the hybrid semiconductor/piezoelectric devices currently in use [6]. Secondly, the large current densities in GaAs/AlGaAs RTSs (up to 10^5 A/cm^2 [7]), combined with the ability of the SAW to synchronize these currents over large areas, make them suitable for power microwave applications.

Thirdly, as a spatially distributed nonlinear system, the SAW-RTS system could enable effects observed in the field of nonlinear optics to be brought into the microwave acoustic domain. Specifically, parametric generation of a SAW by a strong RF pumping field would allow the fabrication of a simple non-dispersive SAW transducer, capable of operating to very high frequencies. This process is the inverse of the process whose results are presented above (for the nonlinear configuration): instead of generating a microwave current (or field) by applying a standing SAW, we apply a strong microwave field to generate two counterpropagating SAW beams. The underlying processes of the interaction between the SAW and a charge density wave are exactly the same in both cases; however, further work remains to ascertain whether this is possible.

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