B-2-04
Extended Abstracts of the 2023 International Conference on Solid State Devices and Materials, Nagoya, 2023, pp83-84

Crosstalk Effect for Acousto-Electric Quantized Current

S. Ota[1,2], J. Wang[3], H. Edlbauer[3], Y. Okazaki[2], S. Nakamura[2], T. Oe[2], A. Ludwig[4], A. D. Wieck[4], T. Kodera[1], C. Bäuerle[3], S. Takada[2], N.-H. Kaneko[2]

[1] Department of Electrical and Electronic Engineering, Tokyo Institute of Technology, Tokyo 152-8550, Japan
[2] National Institute of Advanced Industrial Science and Technology (AIST),
National Metrology Institute of Japan (NMIJ), 1-1-1 Umezono, Tsukuba, Ibaraki 305-8563, Japan
[3] Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France
[4] Lehrstuhl für Angewandte Festkörperphysik, Ruhr-Universität Bochum,
Universitätsstraße 150, 44780 Bochum, Germany
*E-mail: ota.s.ab@m.titech.ac.jp

Abstract(>100 words)

Studies using surface acoustic waves (SAWs) have typically employed SAWs with sinusoidal waveforms. Recently, a technique to generate a single cycle SAW pulse by compressing SAWs in a wide-frequency range using a chirp interdigital transducer (chirp-IDT) has been developed. In this study, we employed this SAW pulse to investigate the effect of electromagnetic crosstalk generated during SAW generation on the quantization of the acoustoelectric current flowing through a one-dimensional channel.

1. Introduction

The generation of surface acoustic waves (SAWs) in piezoelectric materials enables electron transport through the accompanying electric field modulation. SAWs induce potential minima in depleted one-dimensional channels, each of which can trap a single electron. Due to this unique property, SAWs are used in a variety of research fields, for example metrology [1-3]. For the metrology application, crosstalk is a major challenge. Electromagnetic waves emitted by high-frequency parts of the experimental circuit, such as an interdigital transducer (IDT), can be picked up at gates, causing disturbances in the potential of the channel and interfering with the moving SAW potential. To address this problem, methods such as using shields or specially shaped sample holders [1] have been applied to suppress electromagnetic waves. However, it is challenging to completely eliminate crosstalk even with careful shielding. One proposed solution to remove the crosstalk is to modulate the SAW generation signal. However, it is reported that this approach can distort the SAW shape, leading to inaccuracies in electron transport [3]. Recently reported a SAW compressed using a chirp-IDT is capable of electron transport in a single pulse [4]. In this study, we show that by using this method, crosstalk can be completely eliminated.

2. Experiment setup

Device

The experiment is performed within a 4 K pulse tube refrigerator. A Si-modulation-doped GaAs/AlGaAs heterostructure is used to fabricate the sample. The two-dimensional electron gas (2DEG) that is located at 100 nm below the surface has an electron density of $n \approx 2.8 \times 10^{11}\ \mathrm{cm^{-2}}$ and a mobility of $\mu \approx 9 \times 10^5\ \mathrm{cm^2V^{-1}s^{-1}}$. The device contains a quantum wire with a lithographic width of 0.8 μm and a length of 2 μm defined by surface Schottky gates. The 2DEG around the gates is depleted by applying negative voltages to the gates. A chirp-IDT is placed on the sample surface ~1.4 mm to the left of the quantum wire. A broadband IDT as the SAW detector is placed after the quantum wire. The IDTs aperture are 30 μm, and the SAW propagation direction is along [110].

SAW pulse generation

A chirp IDT is an IDT whose cell periodicity changes gradually. Here it is designed to generate SAWs with frequencies ranging from 0.5 GHz to 3.0 GHz. By applying a proper time-varying high-frequency voltage to this IDT, it is possible to generate strongly compressed SAW pulses. The red line in Fig. 1 is a strongly compressed SAW pulse observed by the detector IDT. This waveform is distorted from the actual shape of the SAW passing through the quantum wire due to

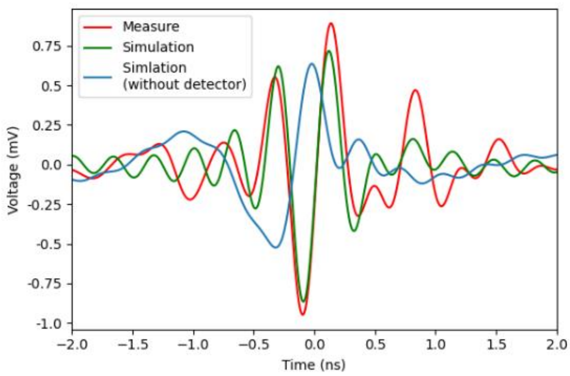

Figure 1 Trace of broadband detector response to compressed SAW generated by chirp IDT (red) with impulse-response simulation (green) and the corresponding SAW shape (blue) derived via deconvolution of the detector response.

the frequency bandwidth of the detector. To find the waveform of the SAW transporting electrons, we performed a simulation using the delta function model. First, we simulated the waveform of the SAW including the detector-IDT component (Fig. 1 green line). Then, by subtracting the detector-IDT component, the waveform of the SAW in the device was simulated (Fig. 1 blue line). The result shows that a SAW pulse with almost a single minimum can be generated.

3. Generating quantized current

SAWs applied to depleted quantum wires can generate acoustoelectric currents that can be controlled by adjusting the gate voltage. Dynamic quantum dots are formed by the lateral confinement of the quantum wire and the longitudinal confinement of the SAW potential. The charging energy of the quantum dots increases as the gradient becomes steeper, and when it becomes sufficiently large, the number of electrons within the quantum dots is discretized. This electron transport generates quantized acoustoelectric currents. Fig. 2 shows that the amount of current generated increases as the SAW power increases. The power of the SAW controls the confinement strength of the electrons in the SAW minimum, which must be sufficient for electron transport at a particular SAW minimum [5]. When the SAW power exceeds a threshold value, the current value is quantized to a constant value and hence a plateau appears. This constant current value is consistent with the quantized value $nef = ne/T_{\text{cycle}}$, which is calculated from the repetition period T_{cycle} of the SAW pulse.

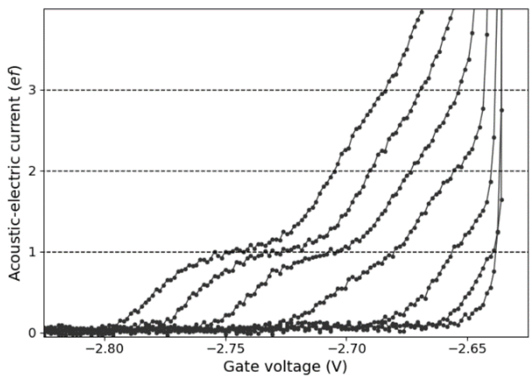

Figure 2 Acoustic-electric current induced by compressed SAW pulse. The SAW amplitude varies from 40 meV to 48 meV (from right to left)

4. Crosstalk effect

When the IDT is excited to generate a SAW pulse, electromagnetic waves are emitted from the IDT. This appears as a crosstalk effect and causes potential fluctuations in structures such as quantum wires. In this device, the SAW reaches the quantum wire about 505 ns after its generation at the IDT. By shifting the timing of the SAW pulse arrival at the quantum wire and the timing of the SAW generation signal input to the IDT, the effect of crosstalk can be eliminated. Fig. 3 compares the acoustic-electric current generated in the quantum wire with and without the effect of crosstalk, where the number of SAW pulses per cycle is the same and the pulse interval is adjusted. It can be seen that interference due to crosstalk affects the electron transport by the SAW pulse and that the plateau does not appear with crosstalk. Such a complete separation of electromagnetic crosstalk is difficult to achieve with a regular IDT used in previous studies because of narrow bandwidth.

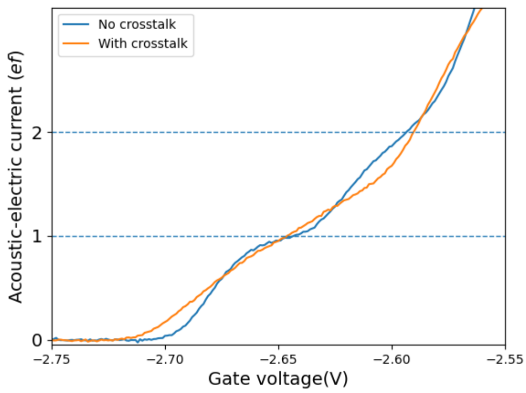

Figure 3 Acoustic-electric current with and without crosstalk.

5. Conclusions

In conclusion, we have observed quantization of acousto-electric currents using chirped SAW pulses. Pulsed SAW is highly flexible because it can generate continuously single electrons but with complete crosstalk isolation. In addition, although electron transport was detected from direct measurement of the current in this study, more accurate detection can be achieved by single-shot detection using a single-electron detector with quantum dots. We consider that this quantized current generation technology using pulsed SAW has the potential to contribute to metrology through its application to single electron pumps.

Acknowledgements

S.O. acknowledge financial support from JST SPRING, Grant Number JPMJSP2106. J.W. acknowledges the European Union’s Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement No 754303. T.K. and S.T. acknowledge financial support from JSPS KAKENHI Grant Number 20H02559. N.-H.K. acknowledges financial support from JSPS KAKENHI Grant Number JP18H05258. C.B. acknowledges funding from the European Union’s H2020 research and innovation programme under grant agreement No 862683.

References

[1] J. M. Shilton, et al., Journal of Physics: Condensed Matter, 8, L531 (1996).
[2] V. I. Talyanskii, et al., Phys. Rev. B, 56, 15180 (1997).
[3] M. Kataoka, et al., Journal of Applied Physics, 100, 063710 (2006).
[4] J. Wang, et al., Phys. Rev. X 12, 031035 (2022).
[5] H. Edlbauer, et al., Appl. Phys. Lett. 119, 114004 (2021).