Single Electron Transport and Device Applications: Acoustic Spintronics

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Introduction

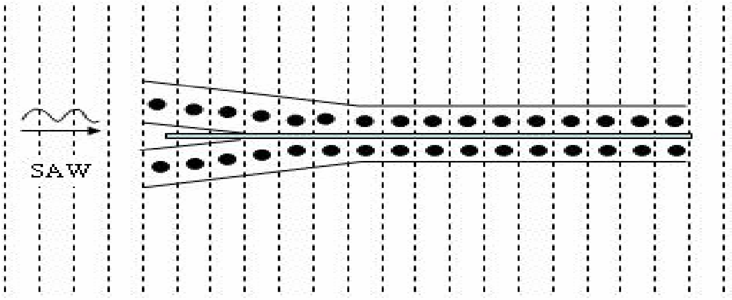
- Recent technology in nanocircuits with a SAW allows us to study electron/hole transport through narrow wires.
- Control of the spin in these experiments may soon occur.
- This would have applications in QC and QIP.
- QC and QIP require stablity of entanglement.
- Possibility of quantum error correction.
- Scalability.
- This paper is concerned with the entaglement of the spins in a SAW nanocircuit using a simple model, and the leakage from the prepared states.

Acoustic Spintronics for Applications in Quantum Optics and Computing

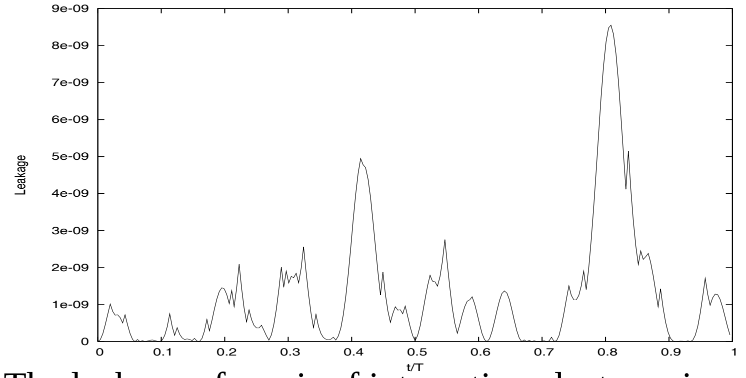
Godfrey Gumbs, Hunter College of CUNY, DMR-0303574

There are now a number of ways for implementing quantum information processing in quantum optics. The essence of these schemes is to build a scalable and efficient quantum computing device. Recently, a novel scheme has been proposed for electron and hole transport and their recombination to produce a single photon source. It uses a new type of nanocircuit in which surface acoustic waves (SAWs) transport the charge. We calculated the quantum entanglement and the leakage from a pair of electrons.

Appl. Phys..Lett. **85**, 2821 (2004).



Two electrons, moving along narrow adjacent channels, are captured by a SAW and form a pair of coupled quantum dots. The full circles dente electrons. .



The leakage of a pair of interacting electrons in adjacent channels as a function of time..

Acoustic Spintronics for Applications in Quantum Optics and Computing

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Education:

One Masters student (Onyeama Osuagwu-Akpunku), one graduate student (Paula Fekete), and one post-doc (Yonatan Abranyos) contributed to this work. Mr. Osuagwu-Akpunku received a Sloan Fellowship, and Ms. Fekete is an NSF Graduate Fellow for 2003-05. Dr. Abranyos received his Ph.D. in 2001 from the City University of New York.

Outreach:

With graduate student Paula Fekete, an additional feature on my website will feature some of the results of our calculations.

The PI and his Condensed Matter Theory group

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Current Quantization

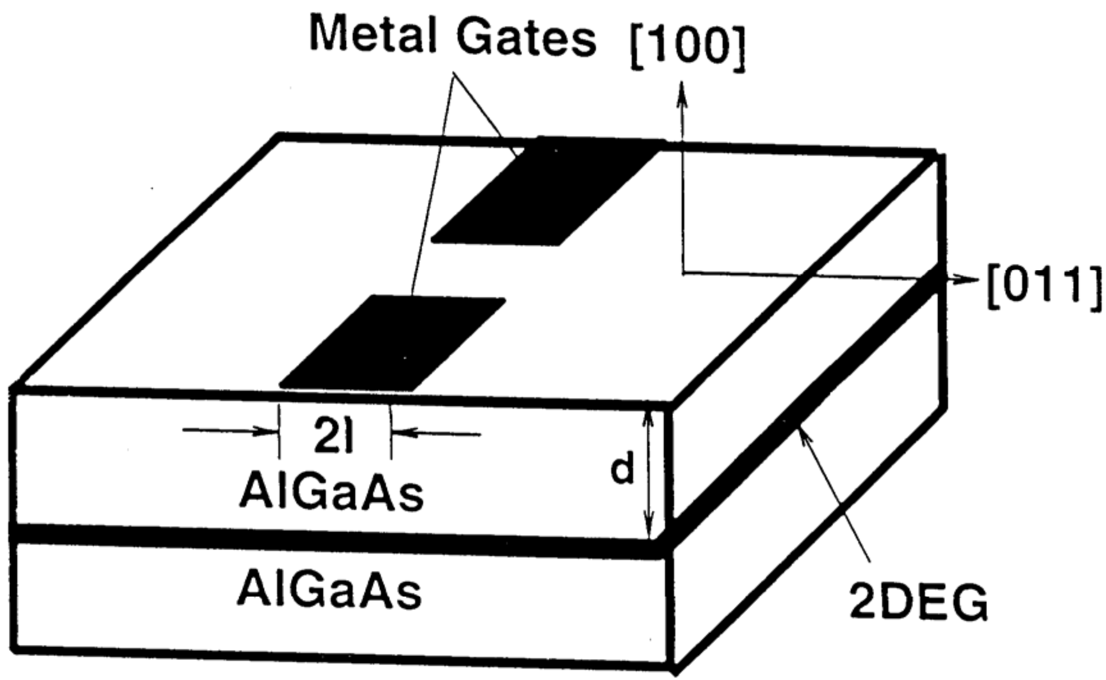
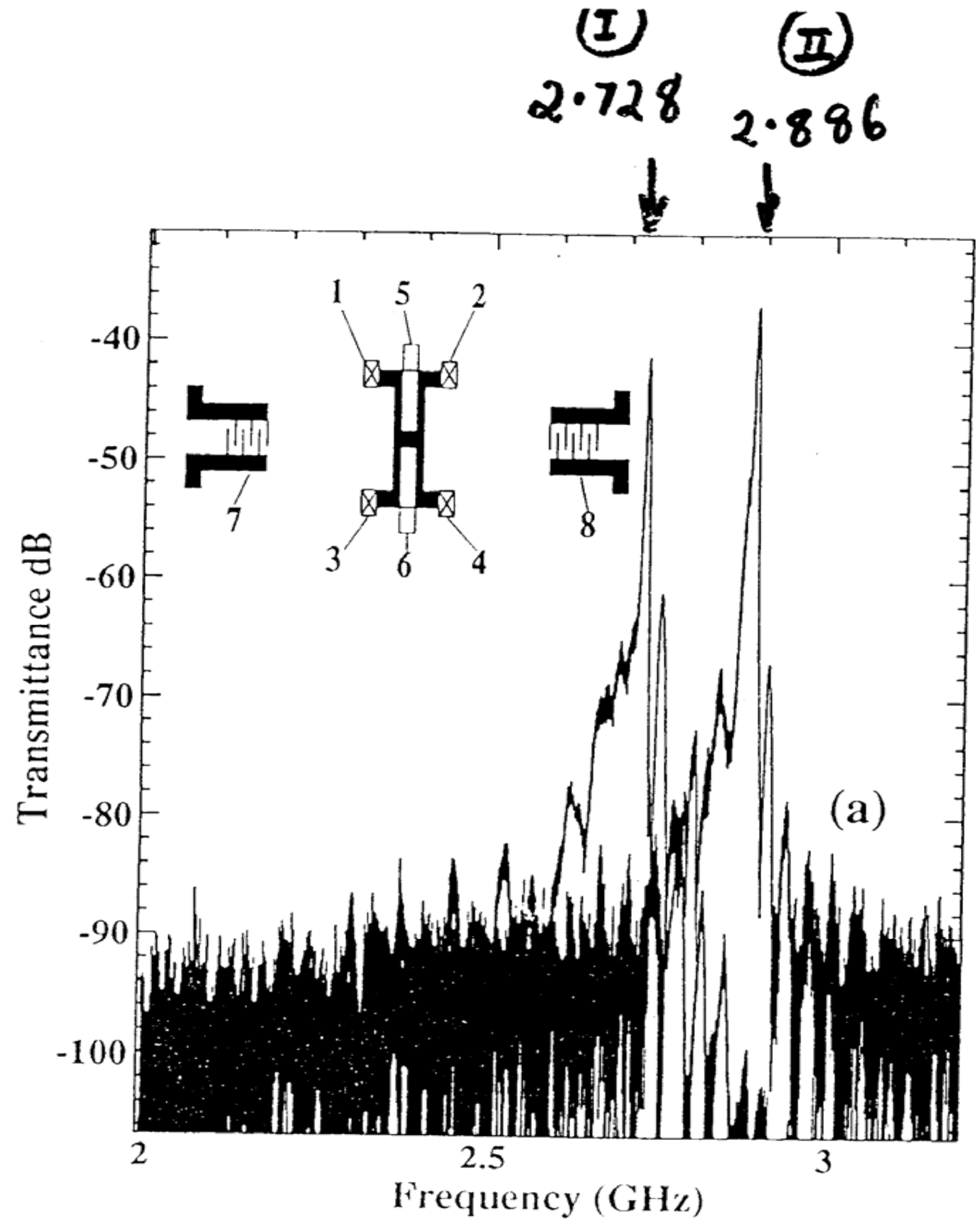
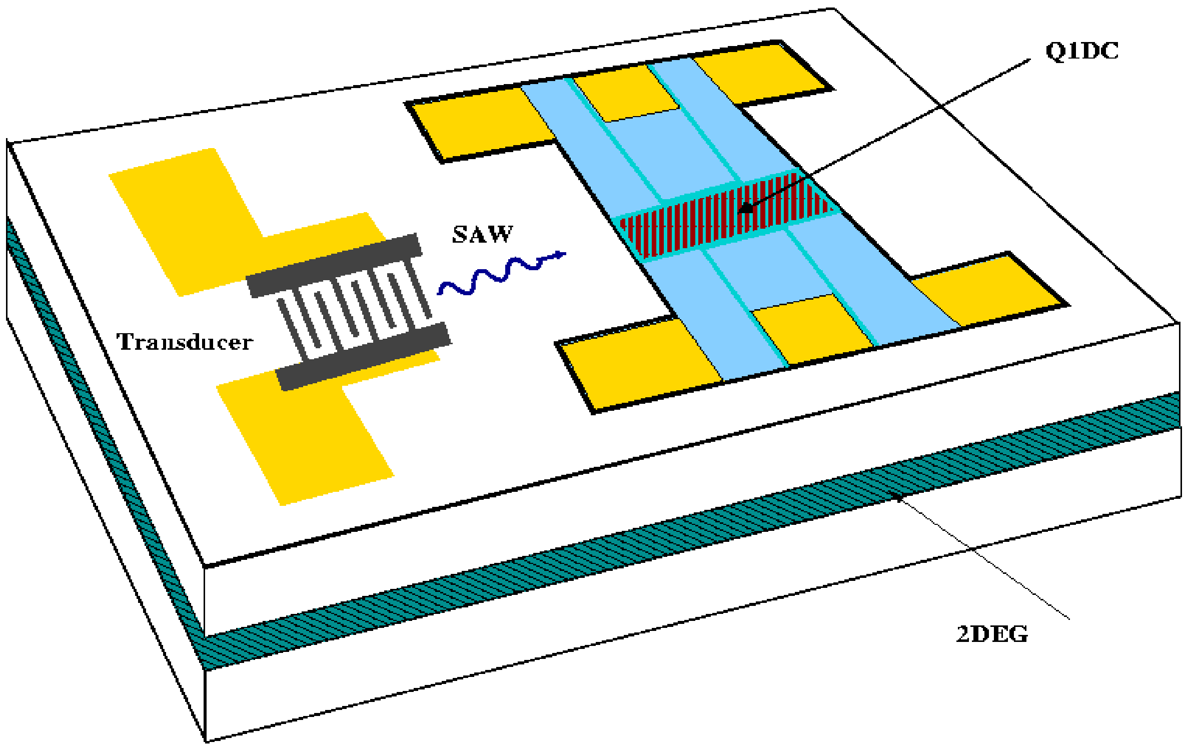


Fig. 1

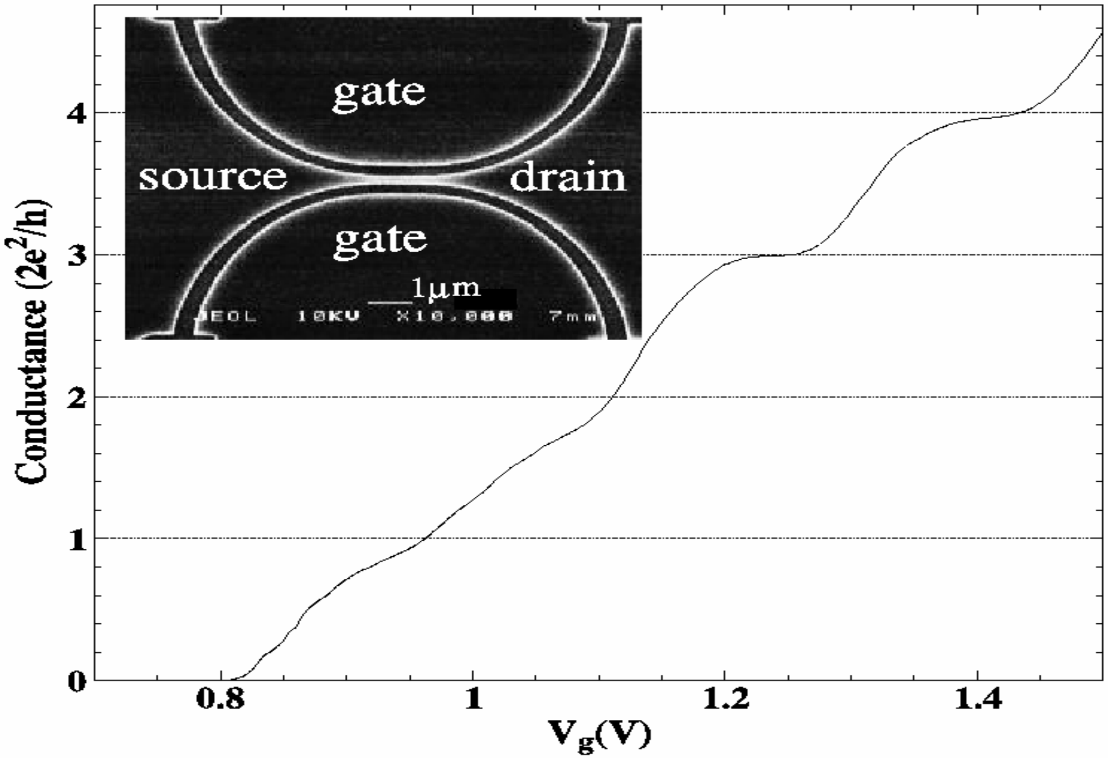


(I)
2·728
(II)
2·886
1
5
2
7
3
6
4
8
(a)
-40
-50
-60
-70
-80
-90
-100
Transmittance dB
2
2.5
3
Frequency (GHz)

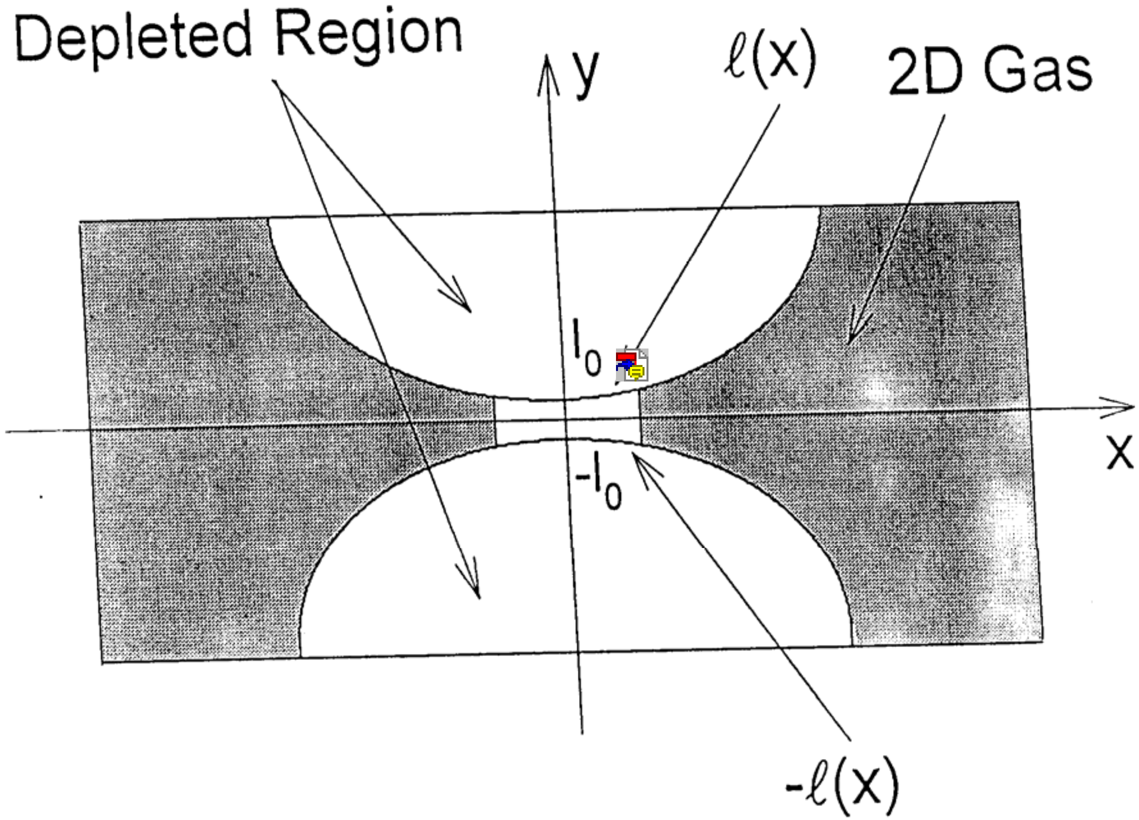
Q1DC

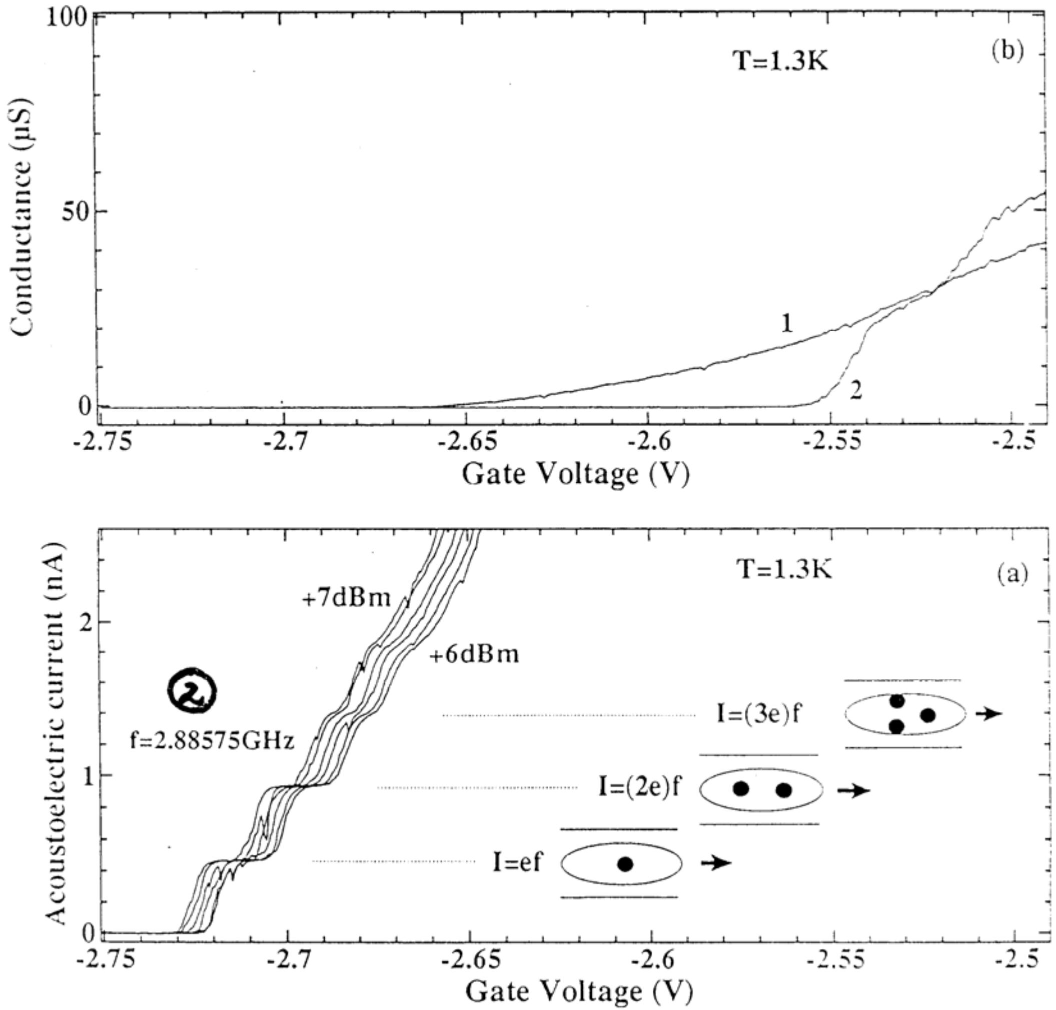


Gates


gate
source
drain
gate
1μm
Conductance ($2e^2/h$)
V_g(V)
0
1
2
3
4
0.8
1
1.2
1.4

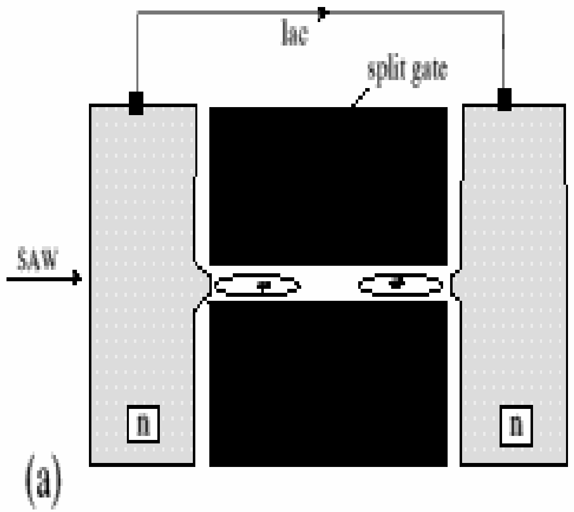
Current Quantization

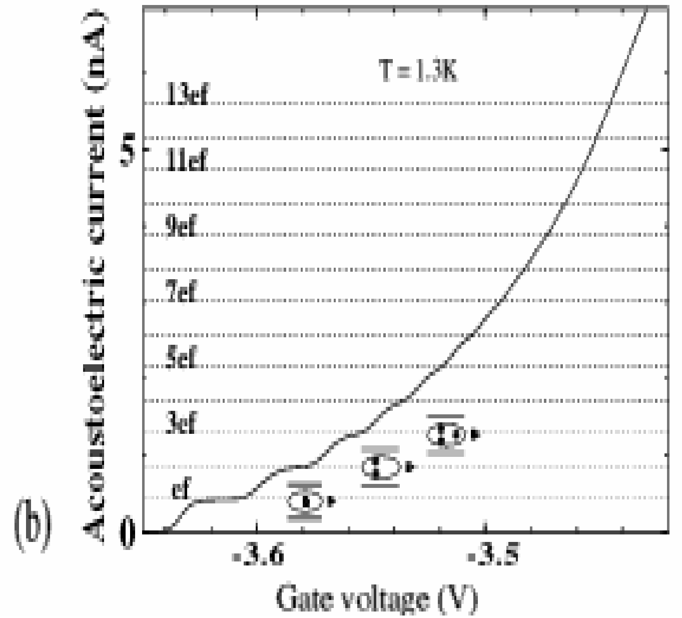




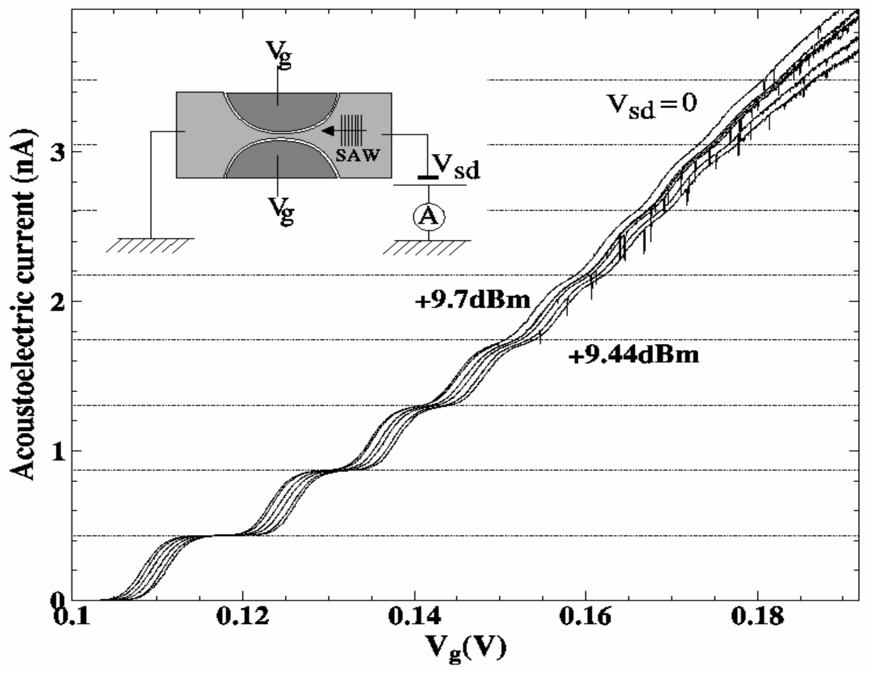
100
50
0
Conductance (μS)
T=1.3K
(b)
1
2
-2.75
-2.7
-2.65
-2.6
-2.55
-2.5
Gate Voltage (V)
Acoustoelectric current (nA)
T=1.3K
(a)
+7dBm
+6dBm
2
f=2.88575GHz
I=(3e)f
I=(2e)f
I=ef
2
1
0
-2.75
-2.7
-2.65
-2.6
-2.55
-2.5
Gate Voltage (V)

Current Quantization





Acoustoelectric Current



CLOSE TO PINCHOFF

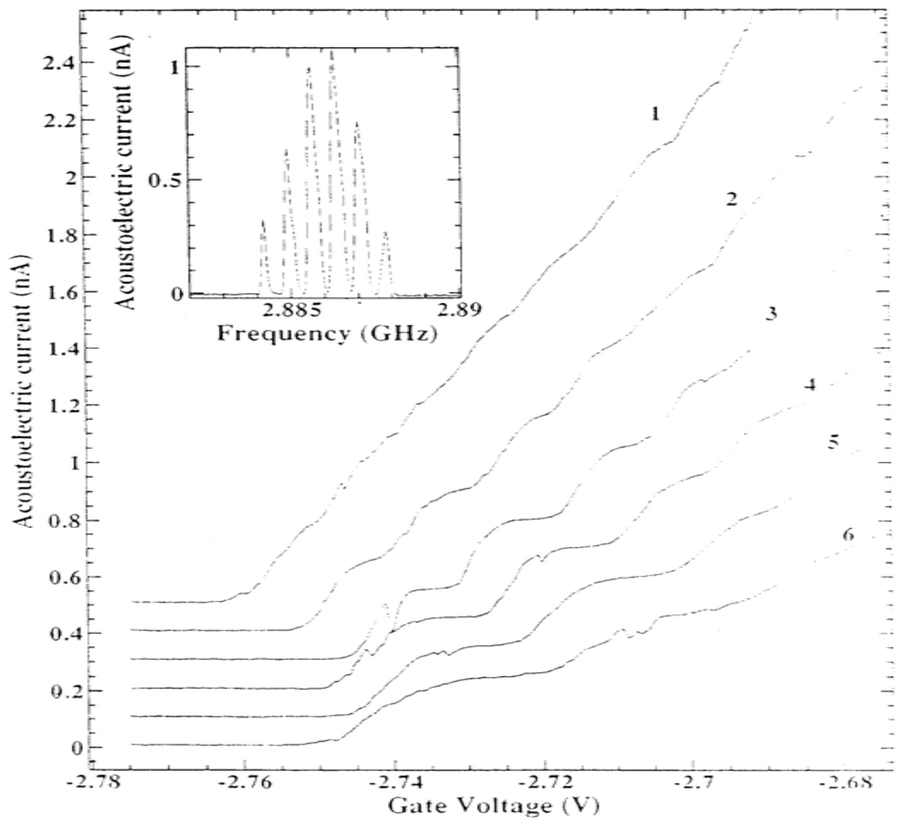
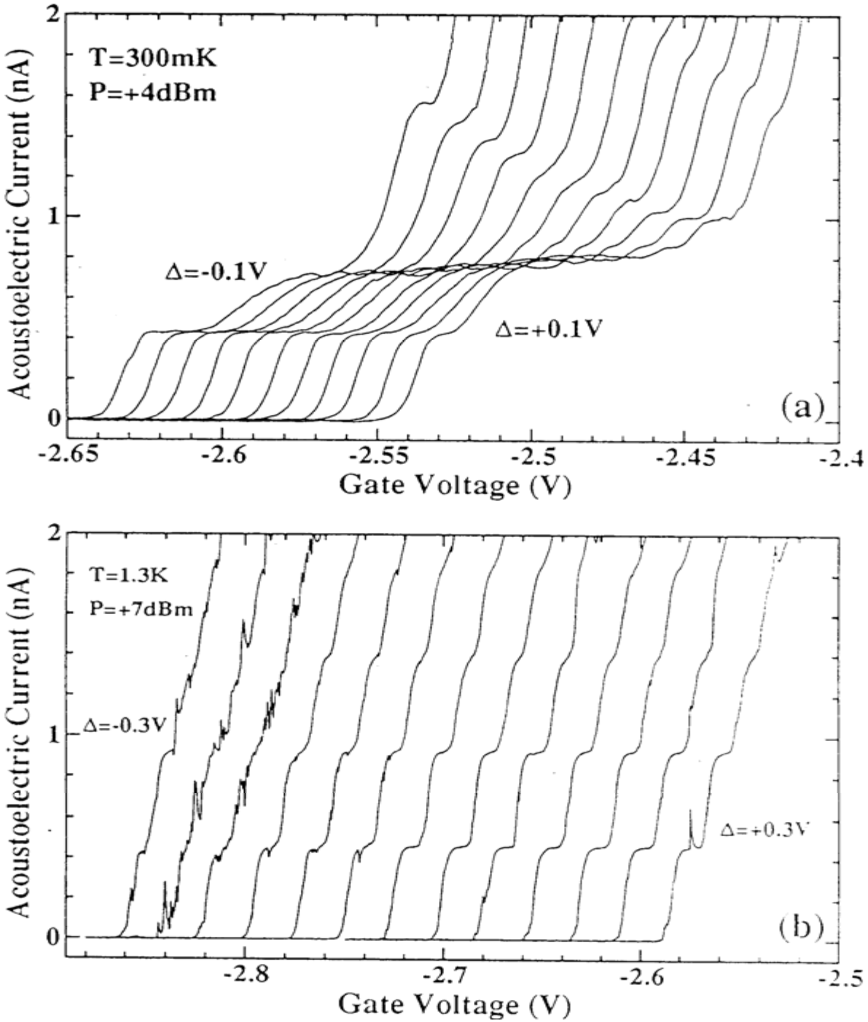
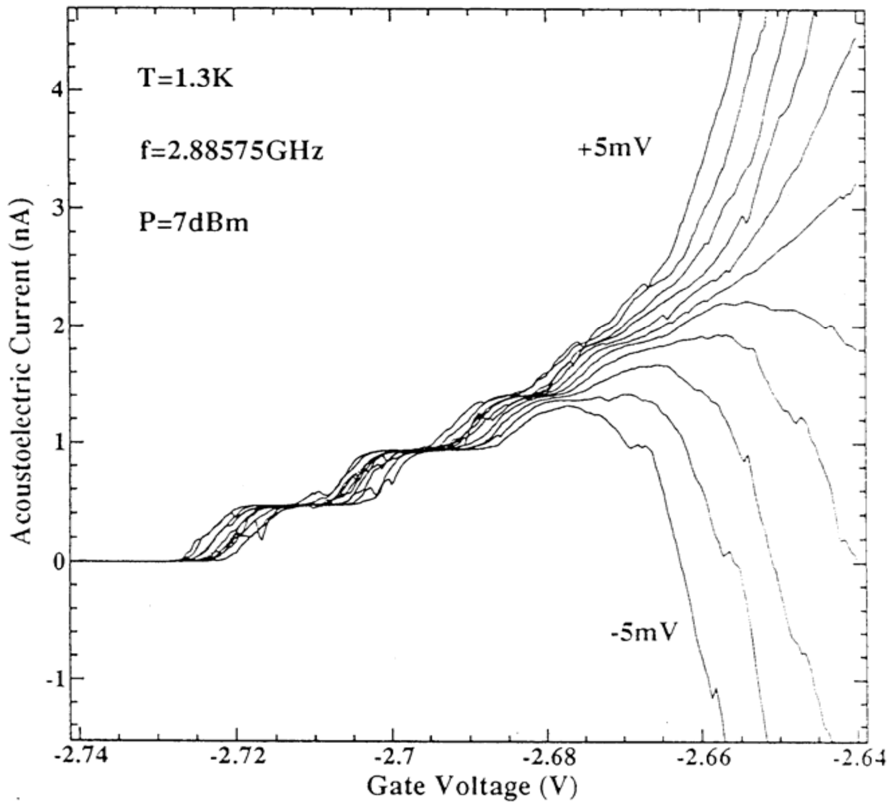


Fig.3

$\Delta = V_{g1} - V_{g2}$.



sample 2.



T=1.3K
f=2.88575GHz
P=7dBm
+5mV
-5mV
Acoustoelectric Current (nA)
4
3
2
1
0
-1
-2.74
-2.72
-2.7
-2.68
-2.66
-2.64
Gate Voltage (V)

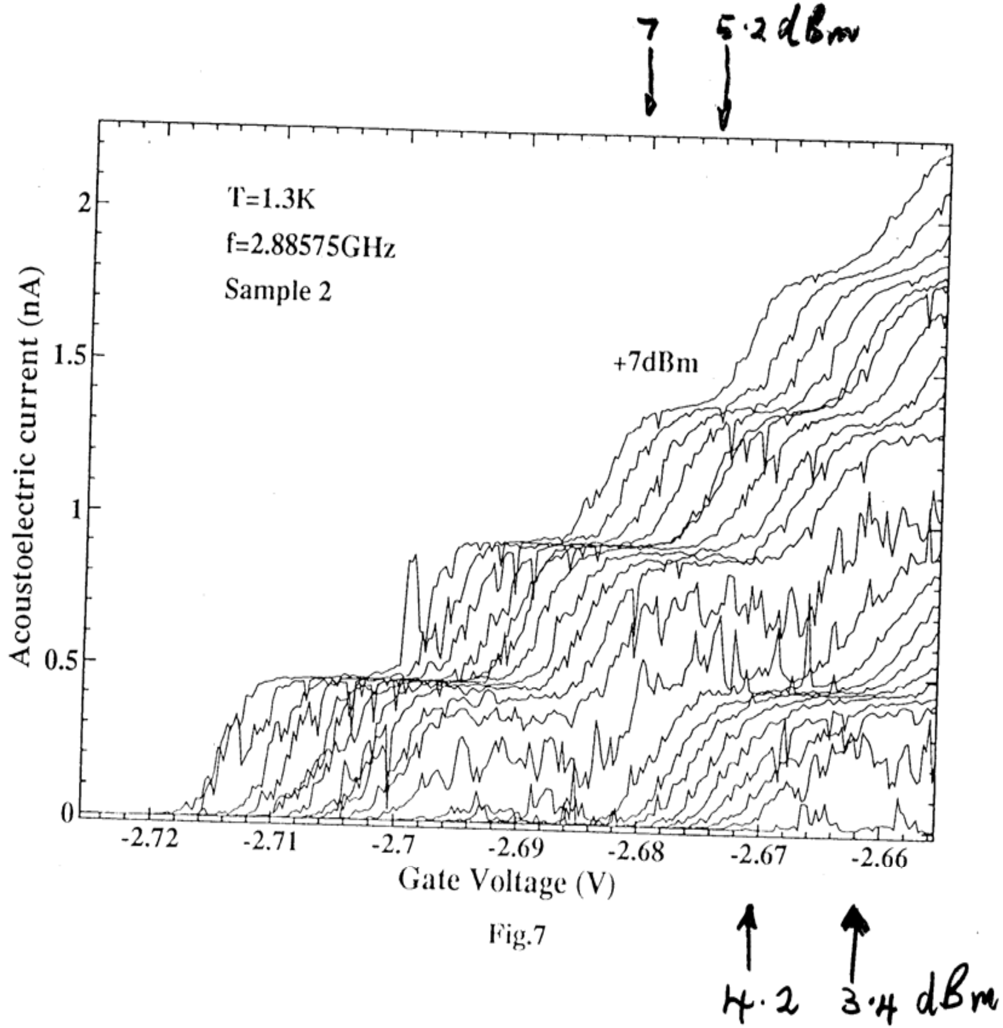
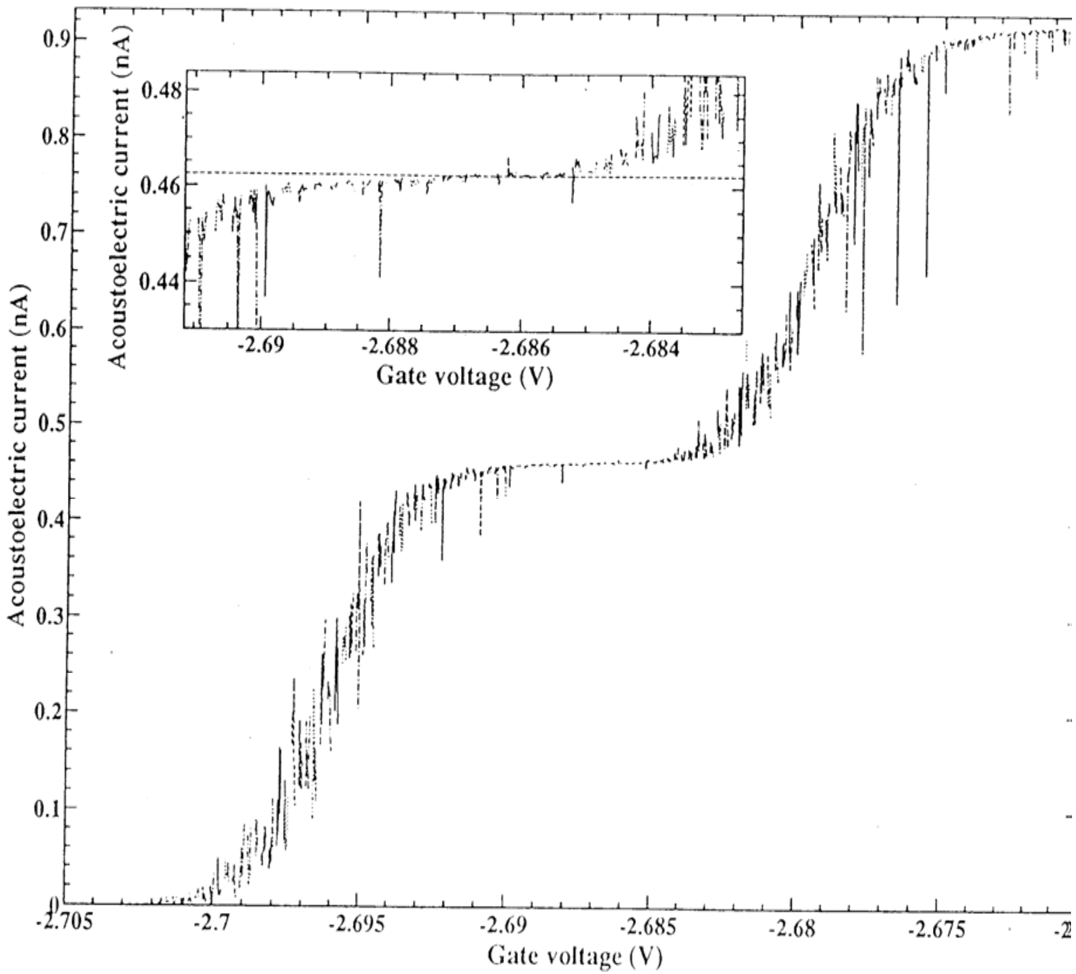

7
5.2 dBm
T=1.3K
f=2.88575GHz
Sample 2
+7dBm
Acoustoelectric current (nA)
0
0.5
1
1.5
2
-2.72
-2.71
-2.7
-2.69
-2.68
-2.67
-2.66
Gate Voltage (V)
4.2
3.4 dBm

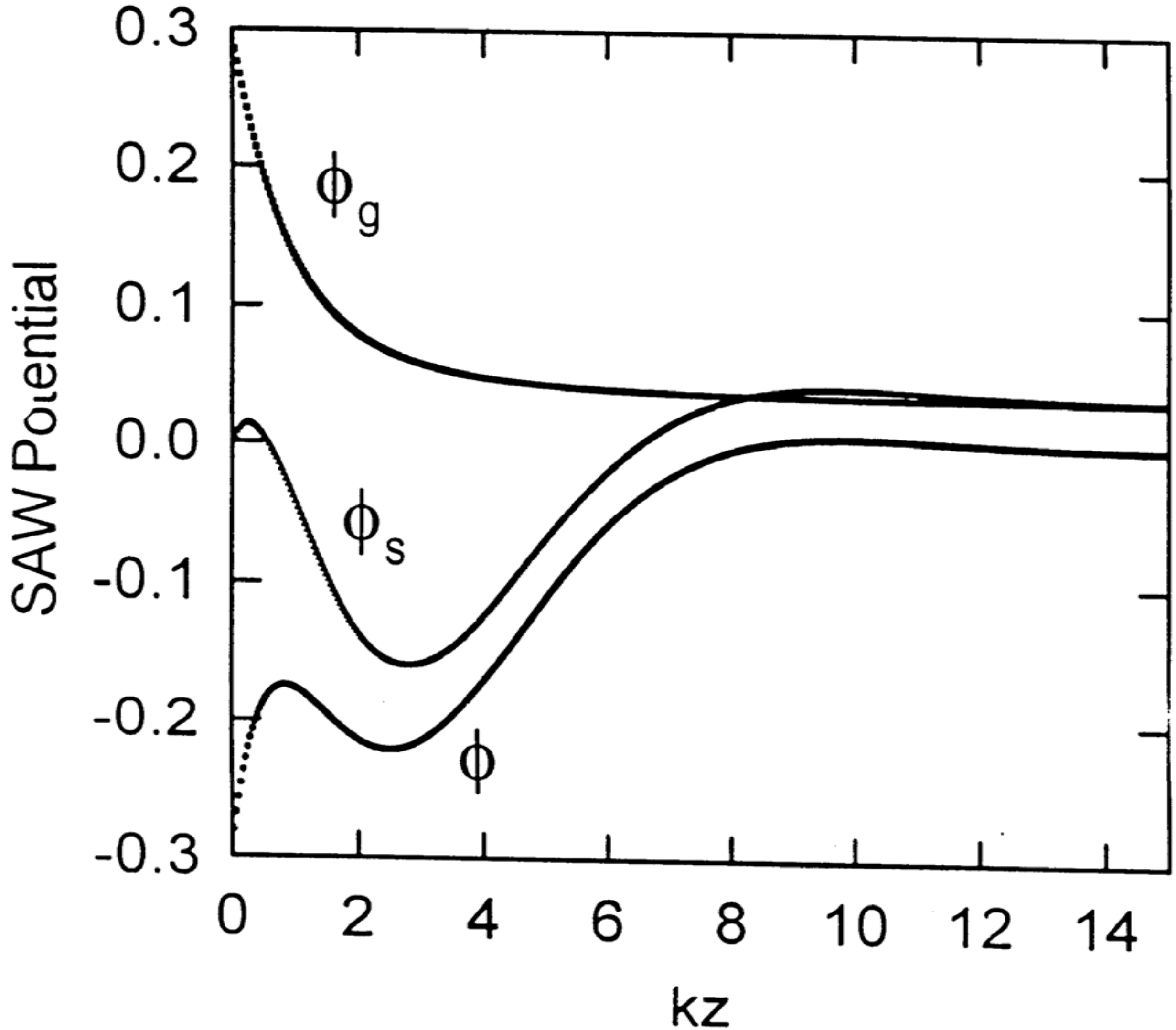
Fig.7



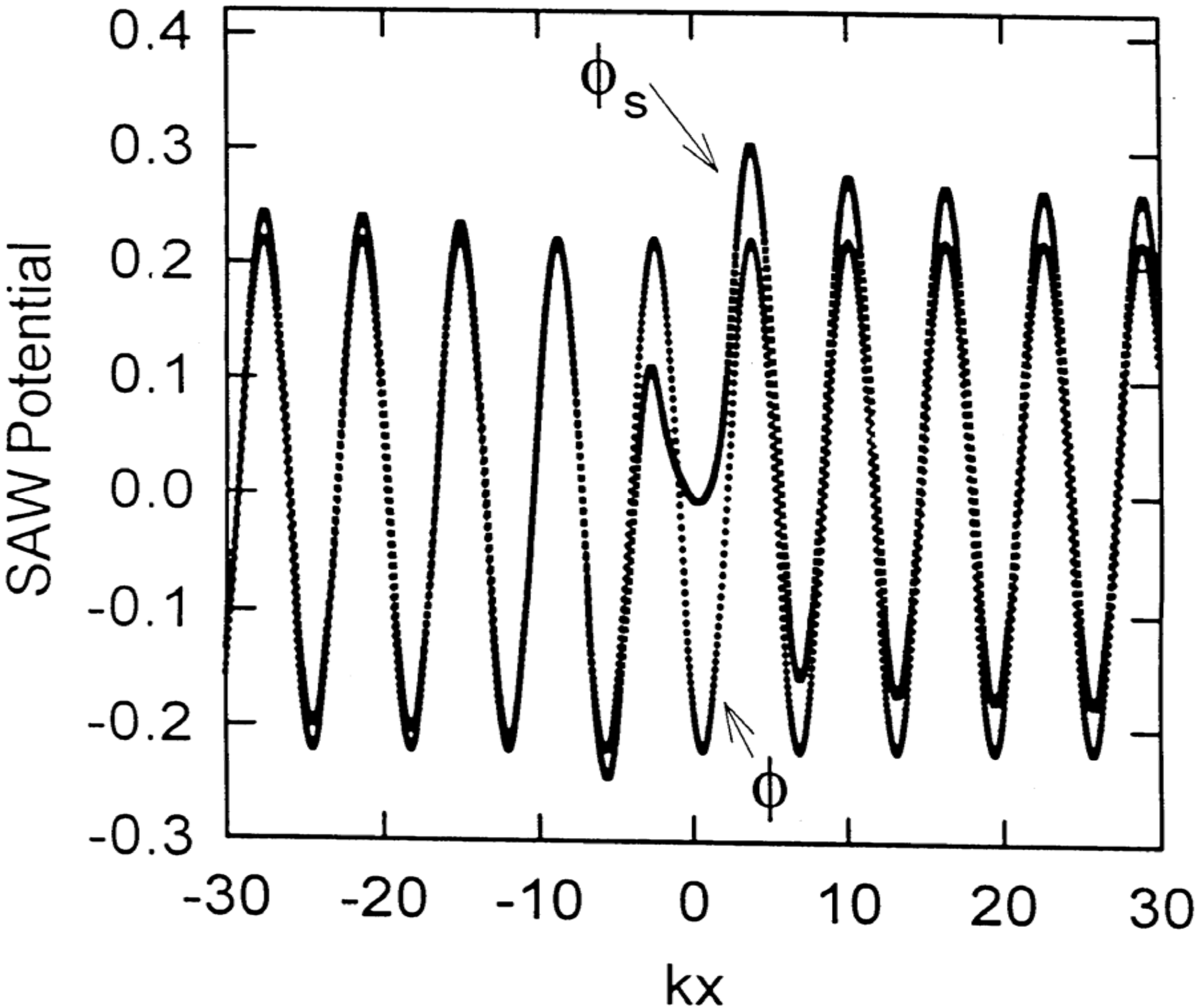
Acoustoelectric current (nA)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-2.705
-2.7
-2.695
-2.69
-2.685
-2.68
-2.675
Gate voltage (V)
Acoustoelectric current (nA)
0.48
0.46
0.44
-2.69
-2.688
-2.686
-2.684
Gate voltage (V)

Fig.8

$$V_{SAW}(x,t) = V_{piezo}(x, z = d, t)$$
$$= \frac{8\pi e_{14} C}{\varepsilon_s} \left[A_1 e^{-\kappa q d} + A_1^* e^{-\kappa q^* d} + A_2 e^{-\kappa d} \right] e^{i\kappa(x - v_s t)}$$



0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
SAW Potential
ϕ_g
ϕ_s
ϕ
0
2
4
6
8
10
12
14
kz

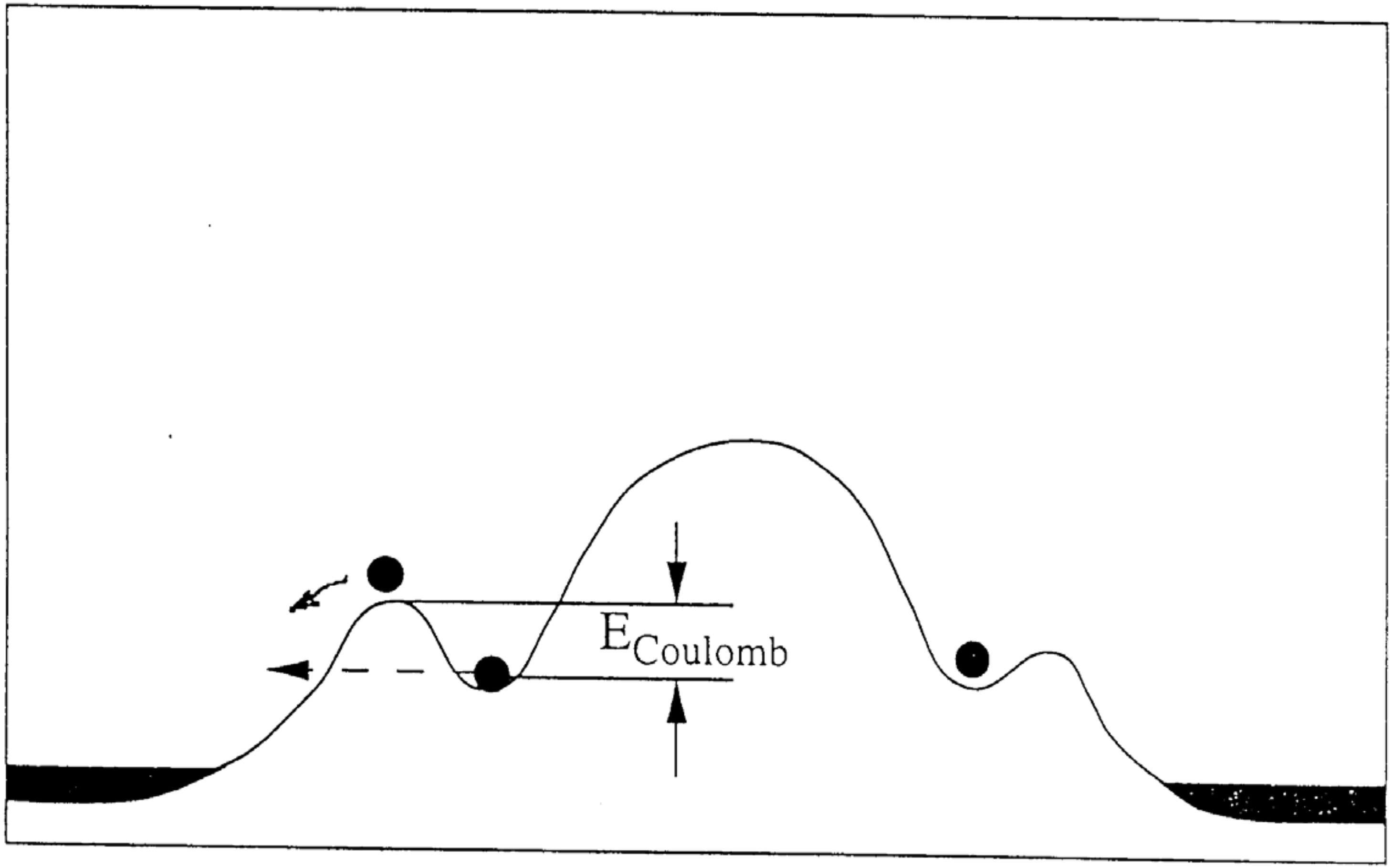


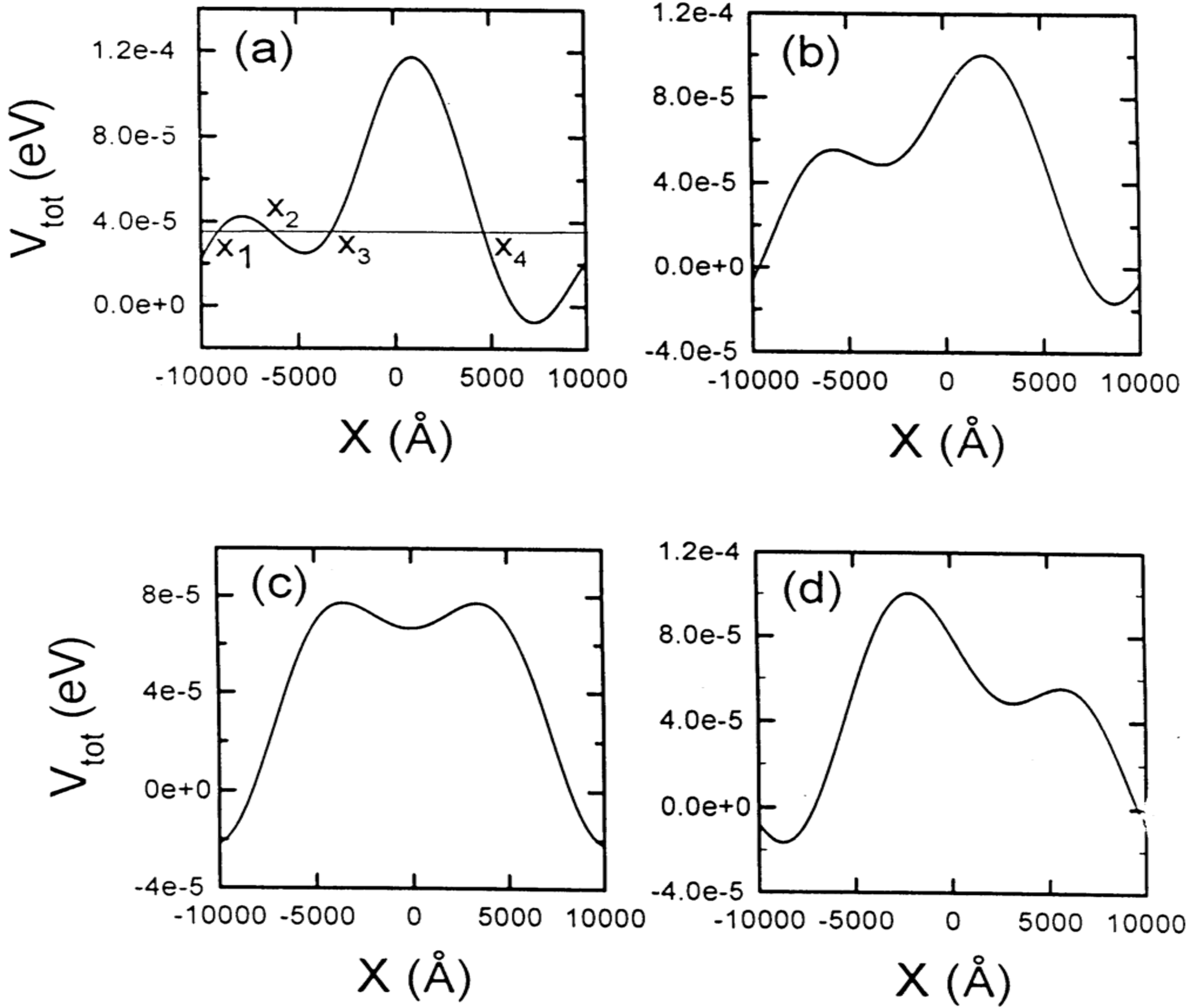
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
SAW Potential
ϕ_s
ϕ
-30
-20
-10
0
10
20
30
kx

Theoretical Formalism

$$\boldsymbol{V_g(x,y) = \frac{V_0}{\cosh^2(x/a)} + \frac{1}{2} m^* \Omega^2 y^2},$$

where the x-axis is chosen along the channel, and the y-axis is across the channel. The parameter V_0 in Eq. (1) determines the effective height of the 1D potential barrier which arises in the quasi-1D channel due to the applied gate voltage.


$E_{Coulomb}$

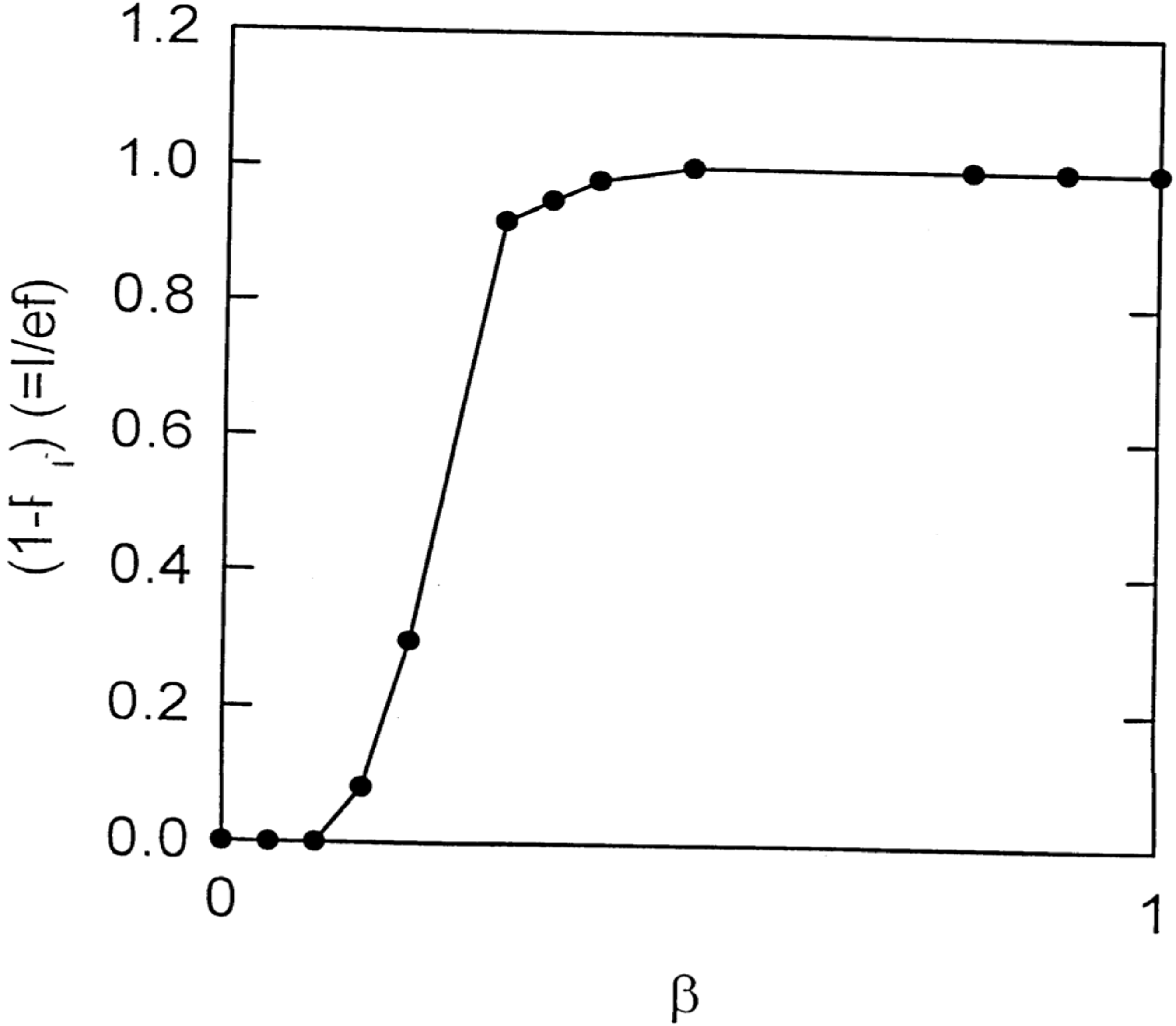

(a)
(b)
(c)
(d)
V_{tot} (eV)
X (Å)
x_1
x_2
x_3
x_4
1.2e-4
8.0e-5
4.0e-5
0.0e+0
-4.0e-5
8e-5
4e-5
0e+0
-4e-5
-10000
-5000
0
5000
10000

Tunneling

The electron tunneling rate form the quantum dot to the 2D region depends on the final density of states, i.e., the DOS in the 2D region and is given by the Fermi golden rule

$$\tilde{P} = \frac{2\pi}{h} \sum_{a,a'} \left| M_{a \to a'} \right|^2 \delta\left(E_a - E_{a'}\right)\left[f_0\left(E_a\right) - f_0\left(E_{a'}\right)\right], \qquad (9)$$

where $M_{a \to a'}$ is the tunneling matrix element, a, a' are the quantum numbers of the initial and final states, and $f_0(E)$ is the Fermi function. In our case, for the quantum dot, $f_0 = 1$ and for the 2D gas, $f_0 = 0$.

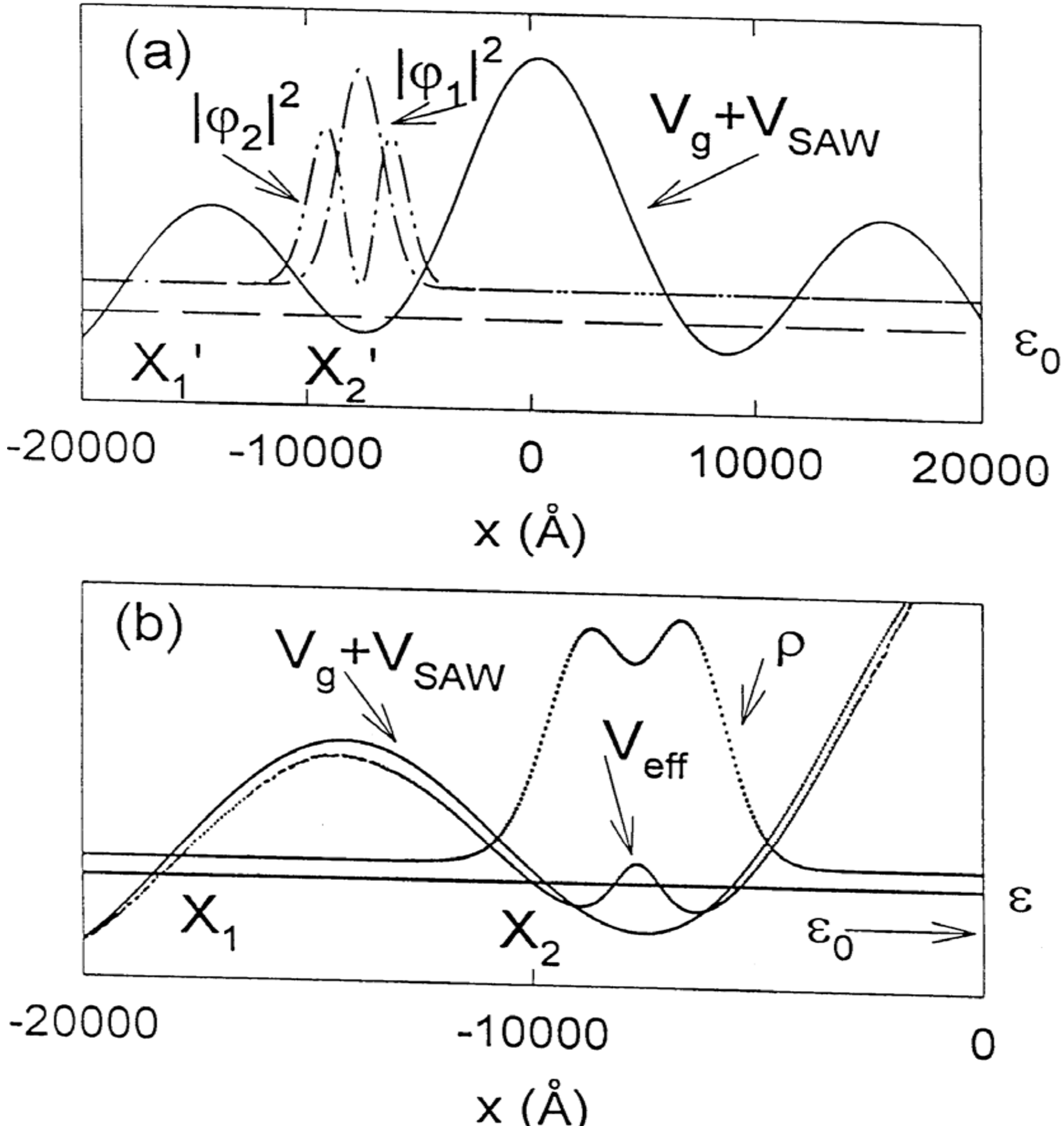

1.2
1.0
0.8
0.6
0.4
0.2
0.0
(1-f i) (=I/ef)
0
1
β

Two interacting electrons

We now consider two interacting electrons in the quantum dot formed by the SAW-induced potential in a narrow channel. The Hamiltonian of the system takes the form

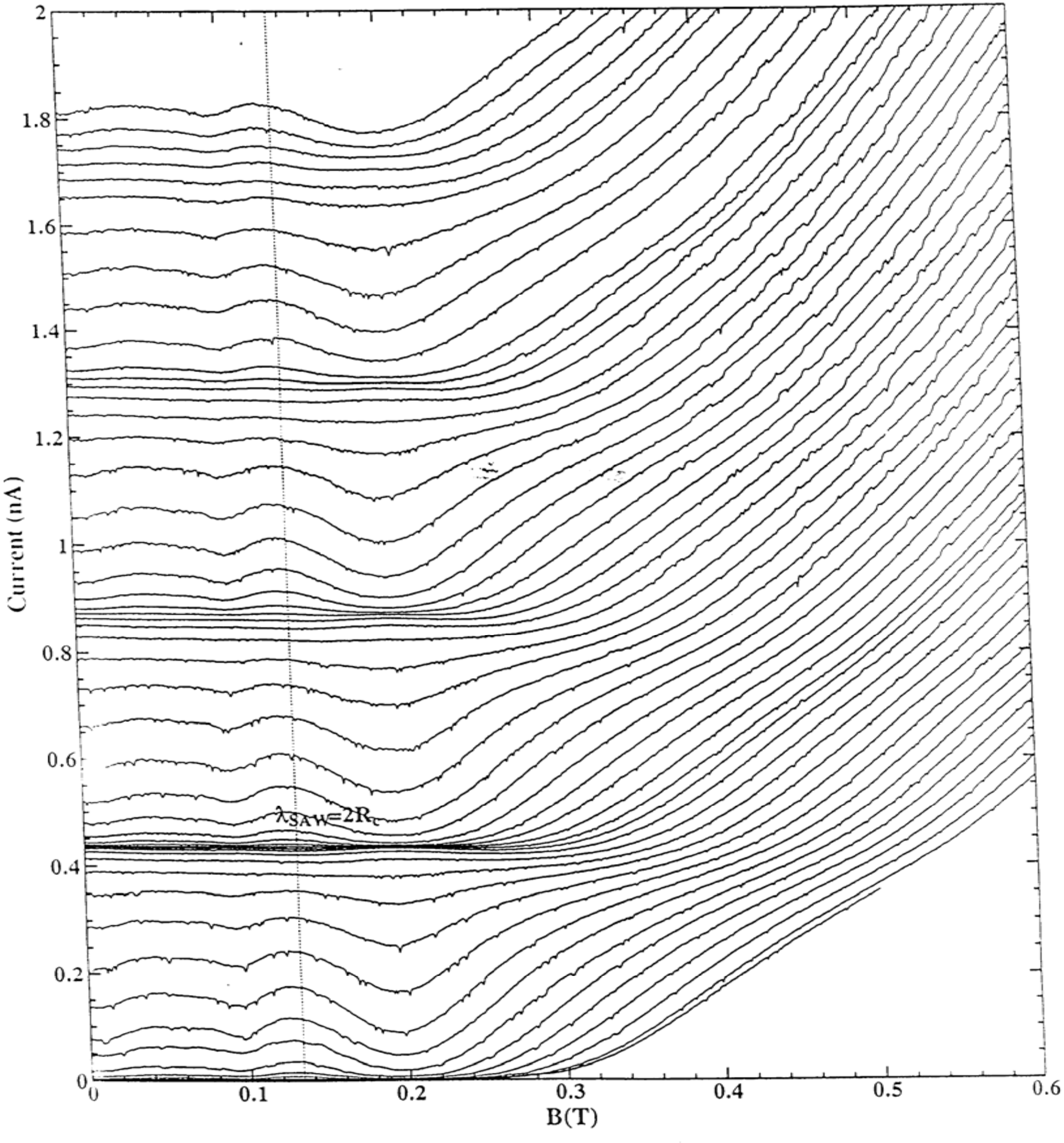
$$\boldsymbol{H} = -\frac{\hbar^2}{2\boldsymbol{m}^*}\left(\nabla_1^{\,2} + \nabla_2^{\,2}\right) + \sum_{i=1,2}\left[\boldsymbol{V}_g(\mathbf{r}_i) + \boldsymbol{V}_{SAW}(\mathbf{r}_i, \boldsymbol{t})\right]$$

$$+\frac{\boldsymbol{e}^2}{\varepsilon_s\left|\mathbf{r}_1 - \mathbf{r}_2\right|} \equiv \boldsymbol{H}_0 + \boldsymbol{H}_{\text{int}},$$

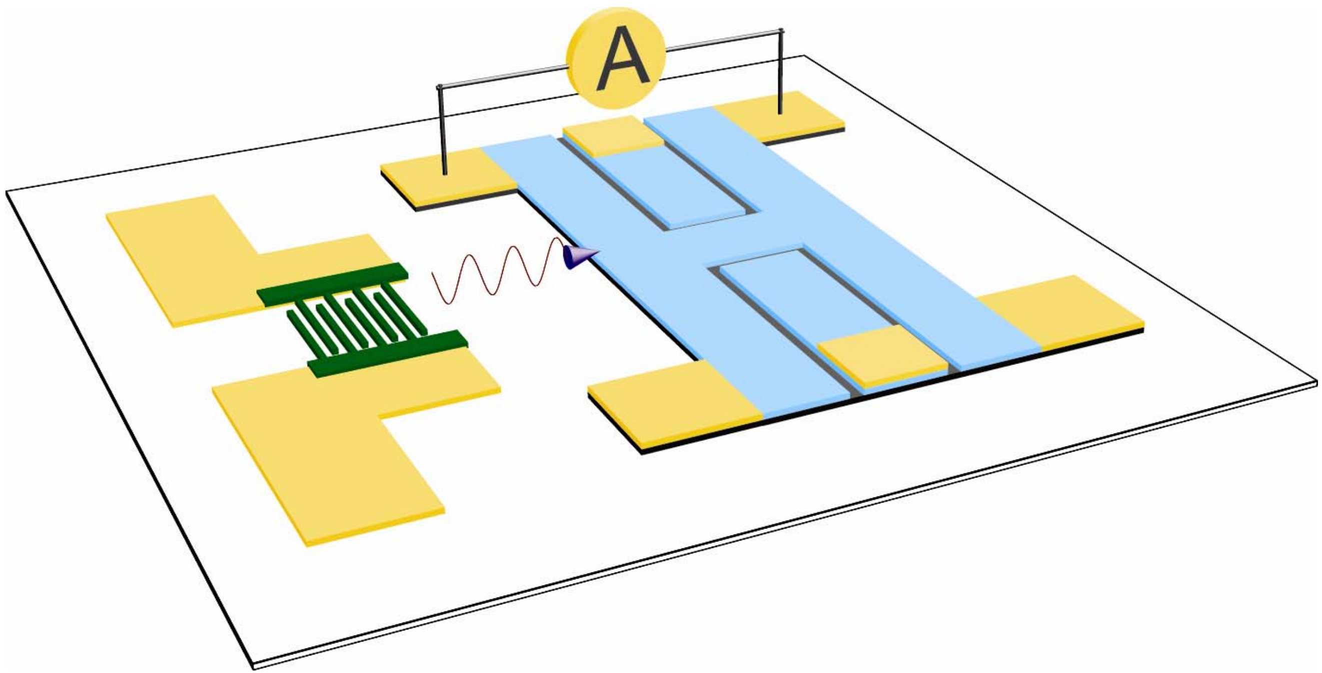


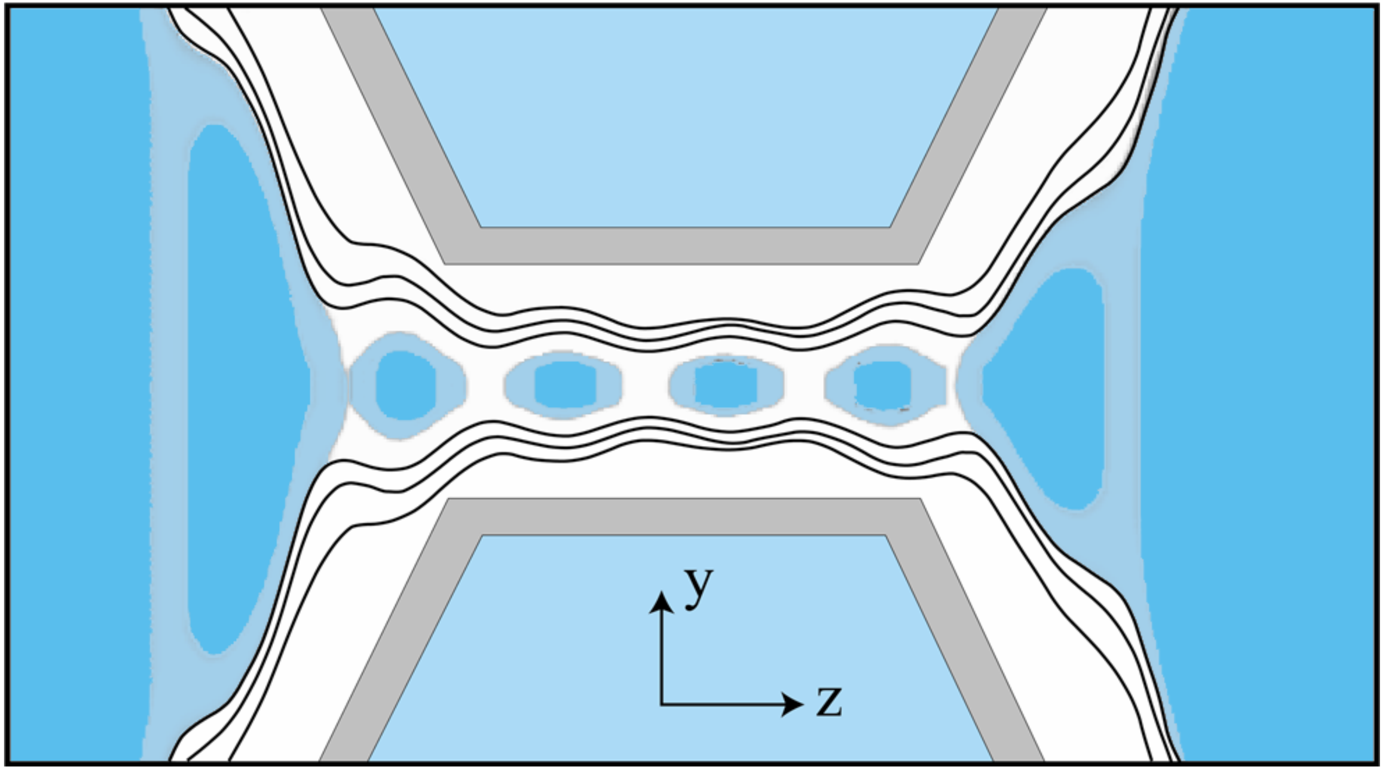
(a)
|φ1|^2
|φ2|^2
Vg+VSAW
ε0
X1'
X2'
-20000
-10000
0
10000
20000
x (Å)
(b)
Vg+VSAW
ρ
Veff
ε
X1
X2
ε0
-20000
-10000
0
x (Å)

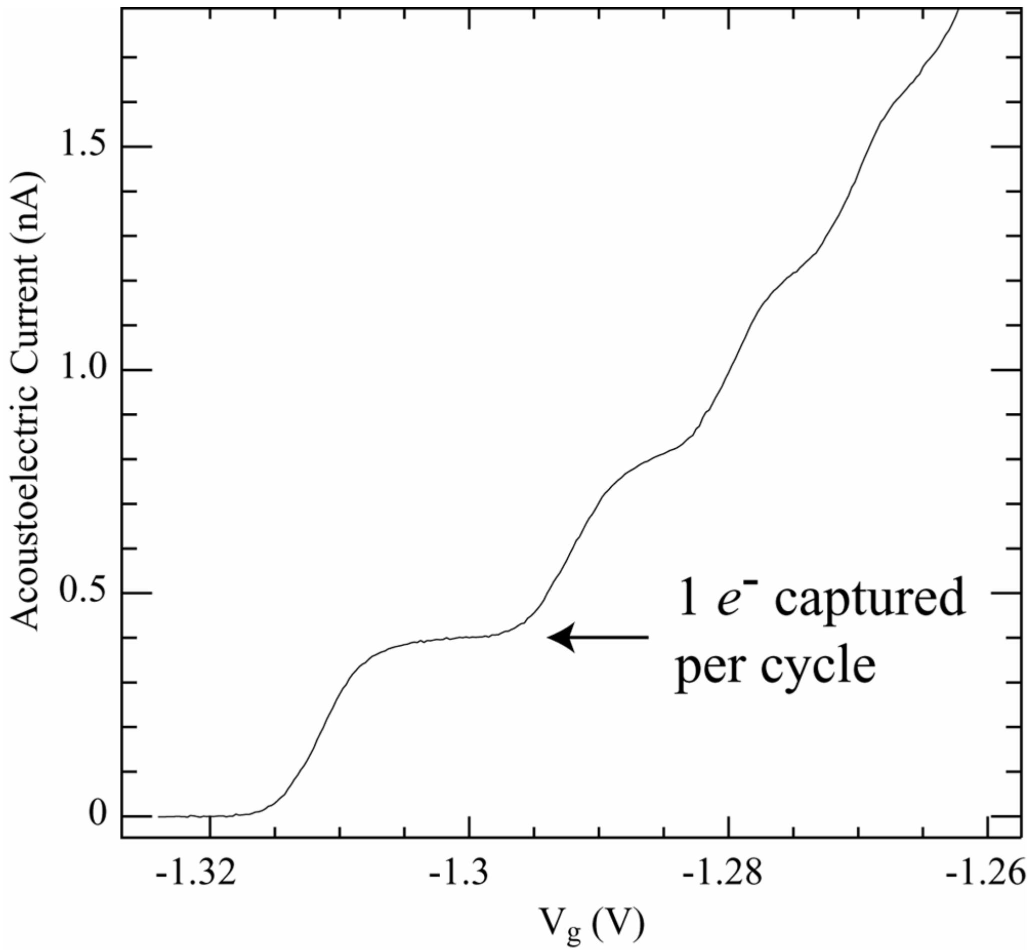
Filename: 72 (Sweeps 1-500 step 4)



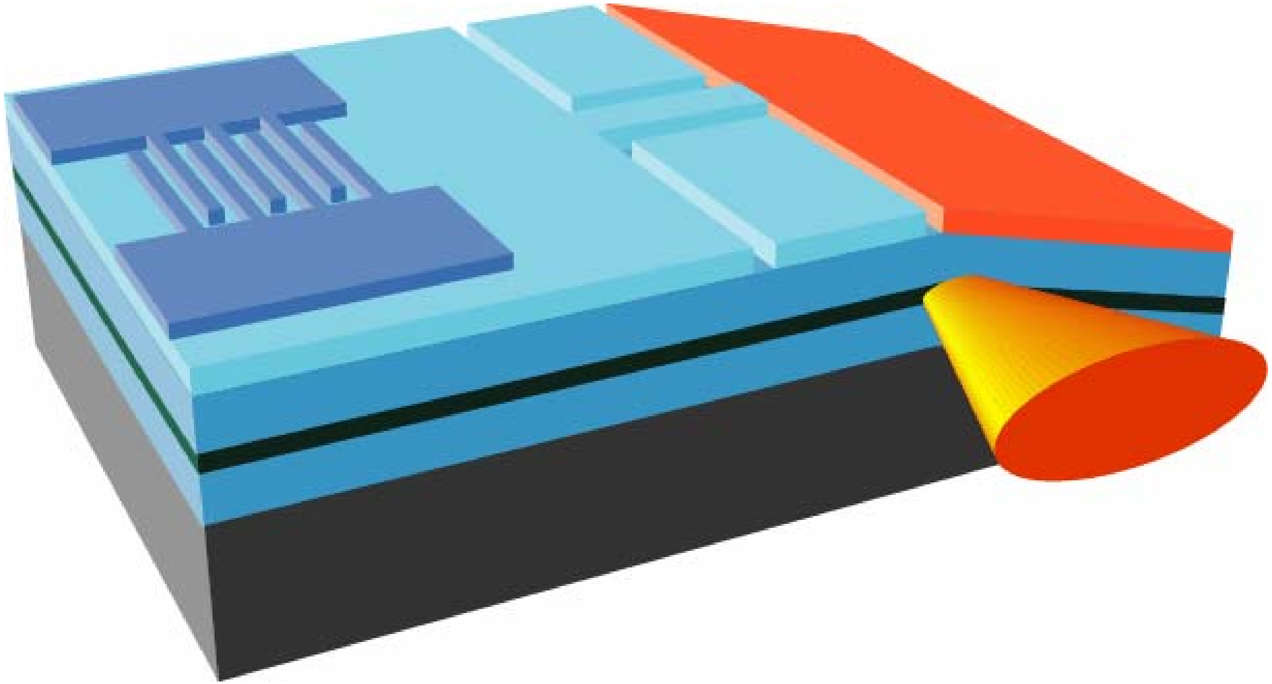
Possible Future Applications

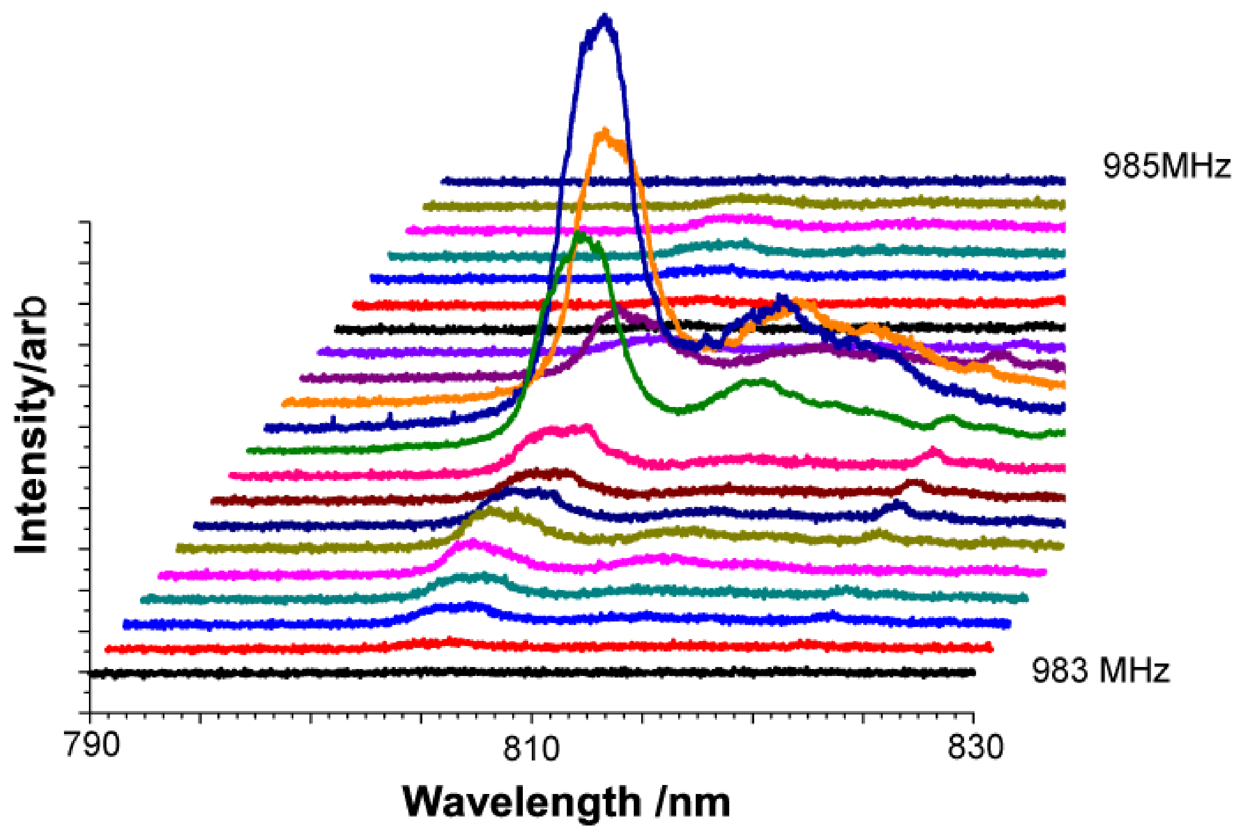


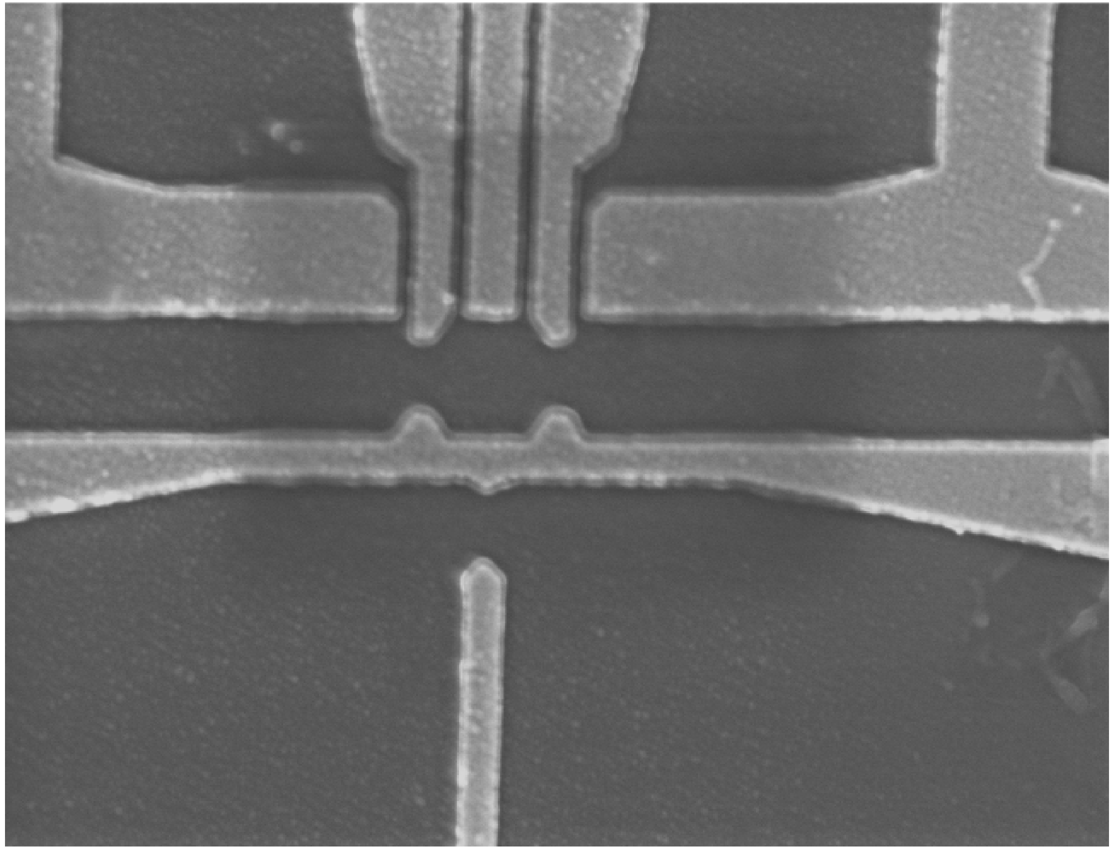

y
z

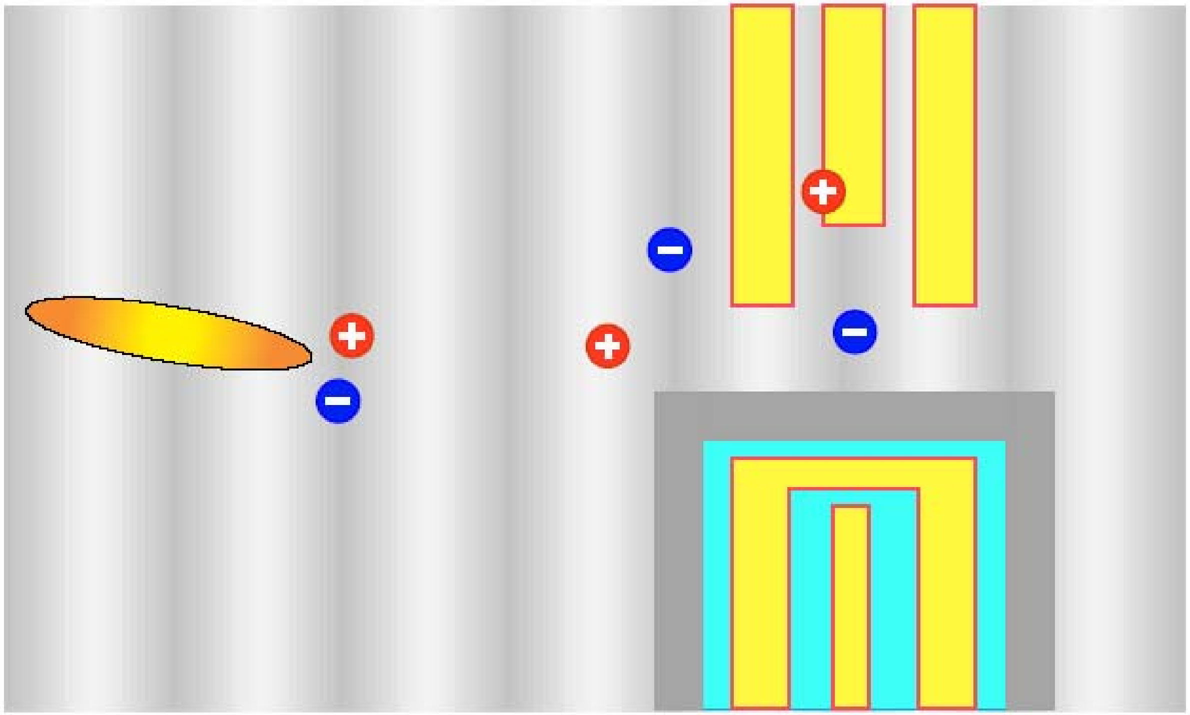


Acoustoelectric Current (nA)
1.5
1.0
0.5
0
-1.32
-1.3
-1.28
-1.26
V_g (V)
1 e⁻ captured
per cycle




985MHz
983 MHz
Intensity/arb
790
810
830
Wavelength /nm





Possible Future Applications

- Quantum information processing: New ideas for single photon sources and single photon detectors are desirable for the development of secure communication links. This security is based on the laws of quantum mechanics. New applications → (a) Photon detectors used in biology and medicine. (b) Various sensors.

Contd.

- Highly desirable is the development of new unconventional experimental techniques to study various nano-objects including those mentioned above especially techniques for studying dynamical properties of nanostructures are required. → One such technique could be based on high frequency surface acoustic waves (SAWs).

Optoelectronic Nanocircuits on GaAs

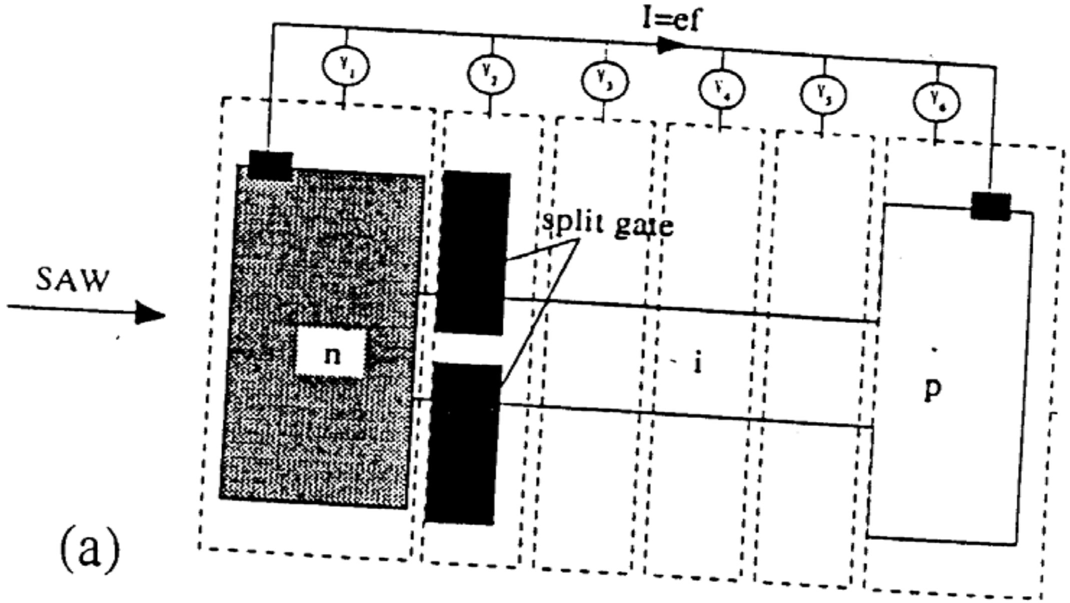
- Control of charge movement down to a single electron and of photon emission down to a single photon.
- In these circuits, charge is transported along “quantum wires” in the form of nanometer-sized packets by high-frequency surface acoustic waves (SAWs) --- $f \sim 3GHz$, $\lambda \sim 1\mu m$, $T_t = 300ps$.
- Single-photon source produces single photons or pulses of a fixed number of photons **On Demand**.

Possible Applications for Single-Photon Source

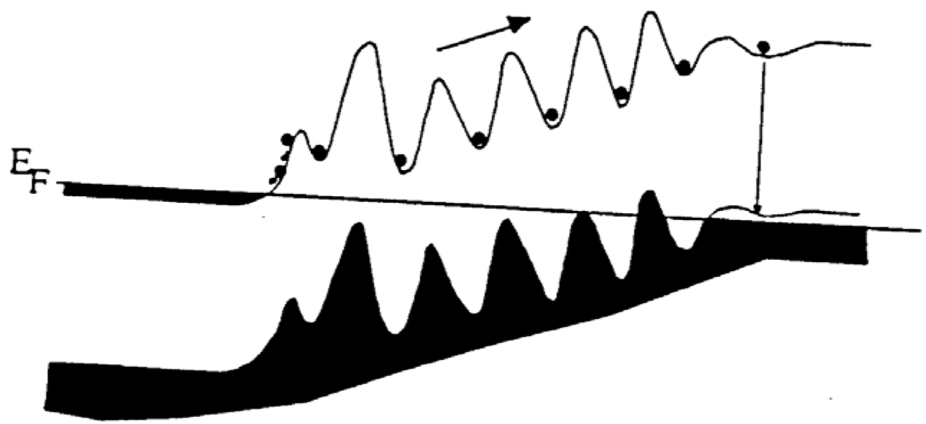
- Quantum cryptography → secure optical communication (military, diplomatic and commercial applications) – information is carried by single quantum states.
- Principle: → send polarized light through optical fibers or free space.
- A single photon source does not yet exist → highly attenuated laser pulses are employed.

Possible Applications for Single-photon Source (Contd.)

- Weak coherent light may contain any number of photons (with an average of less than one) rendering quantum cryptography insecure.



(a)



(b)

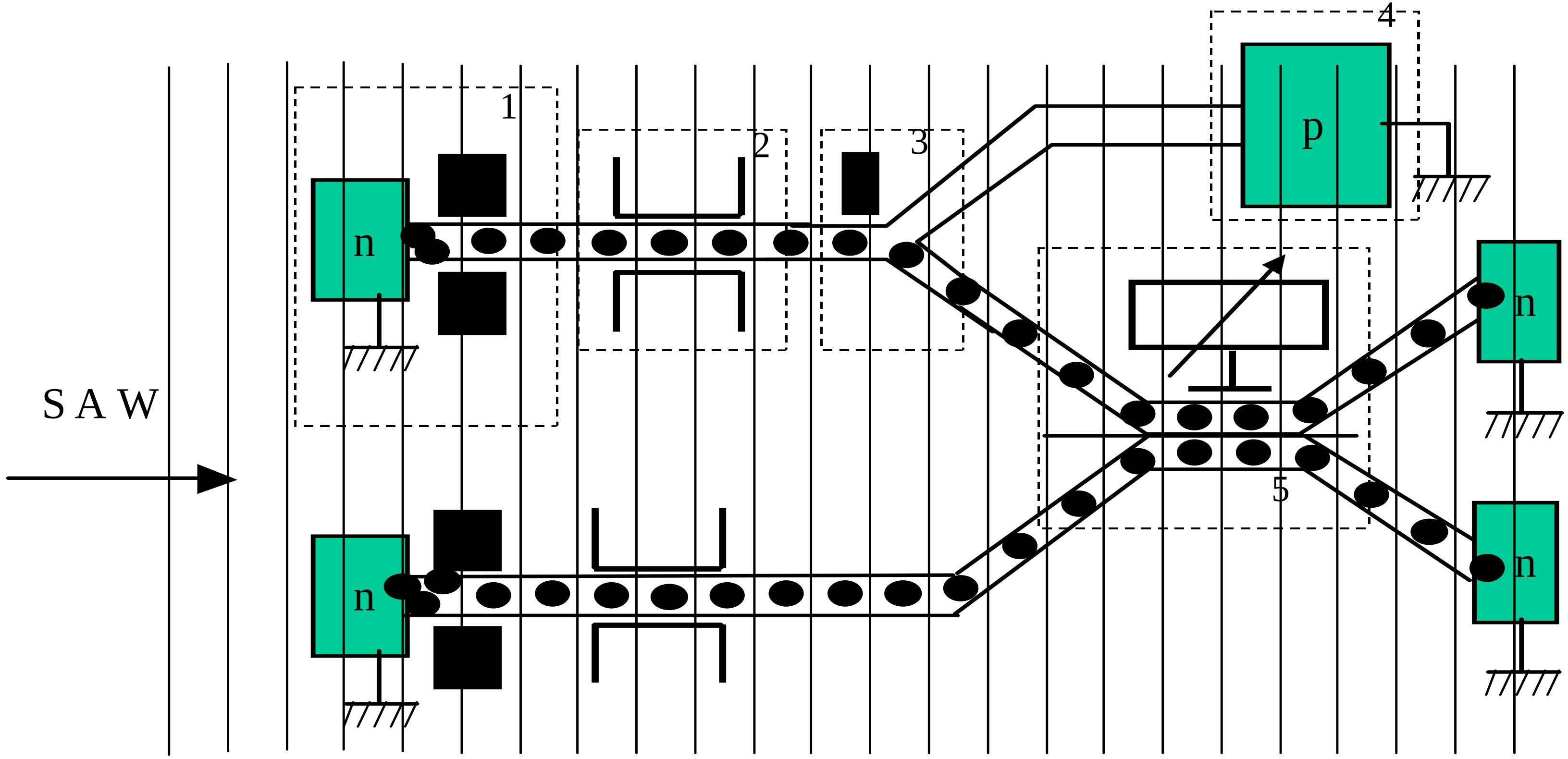


Fig.2

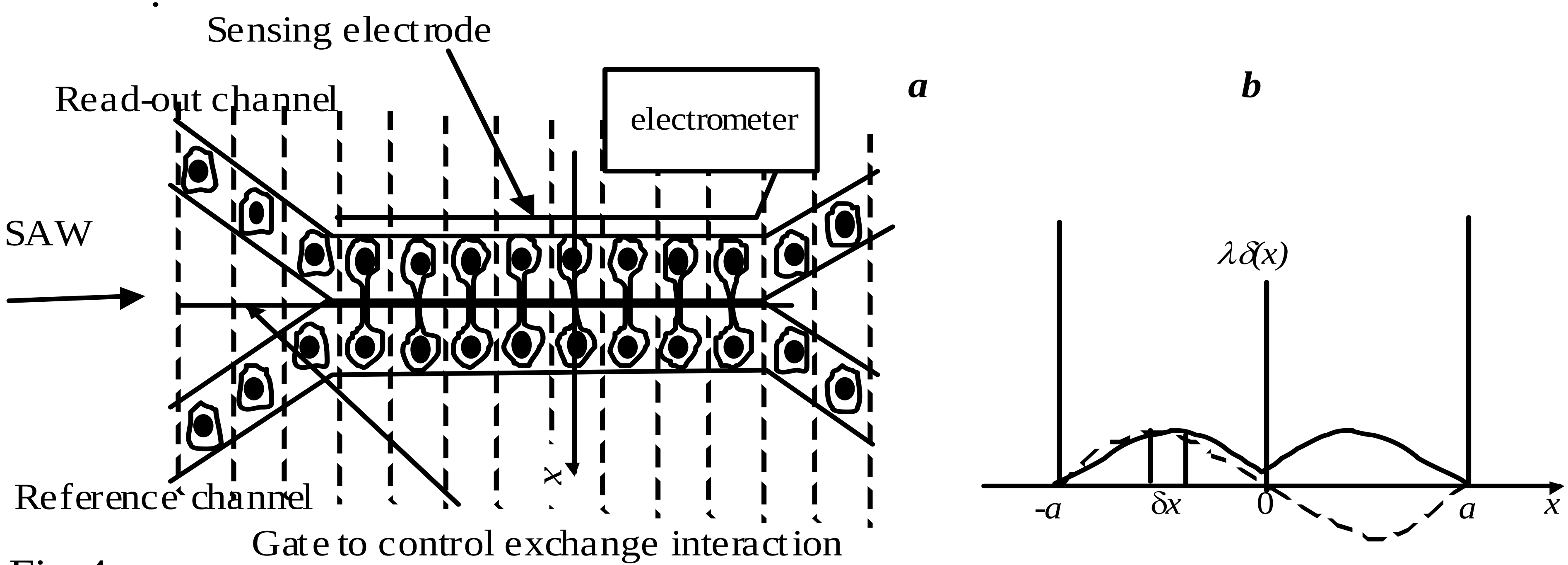
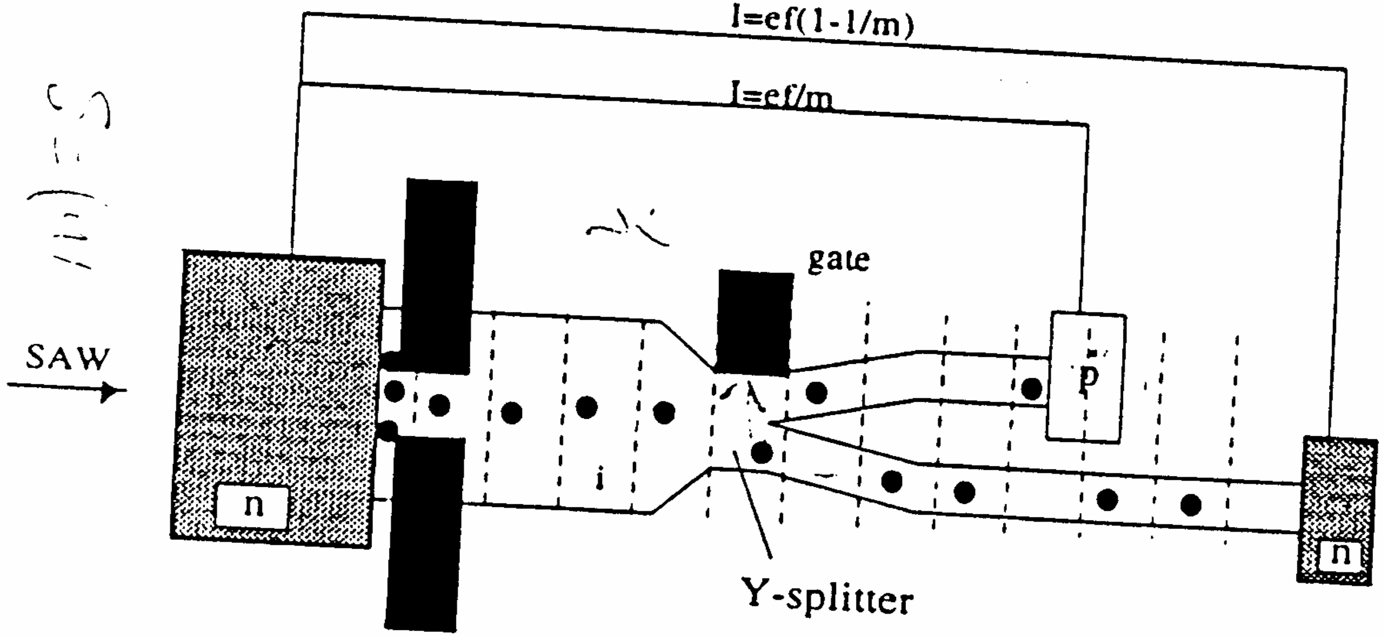
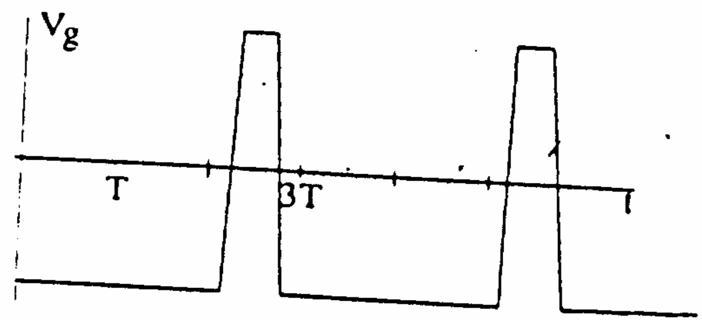

Sensing electrode
Read-out channel
electrometer
a
b
SAW
$\lambda\delta(x)$
x
Reference channel
Gate to control exchange interaction
-a
δx
0
a
x

Fig.4



(a)



(b)

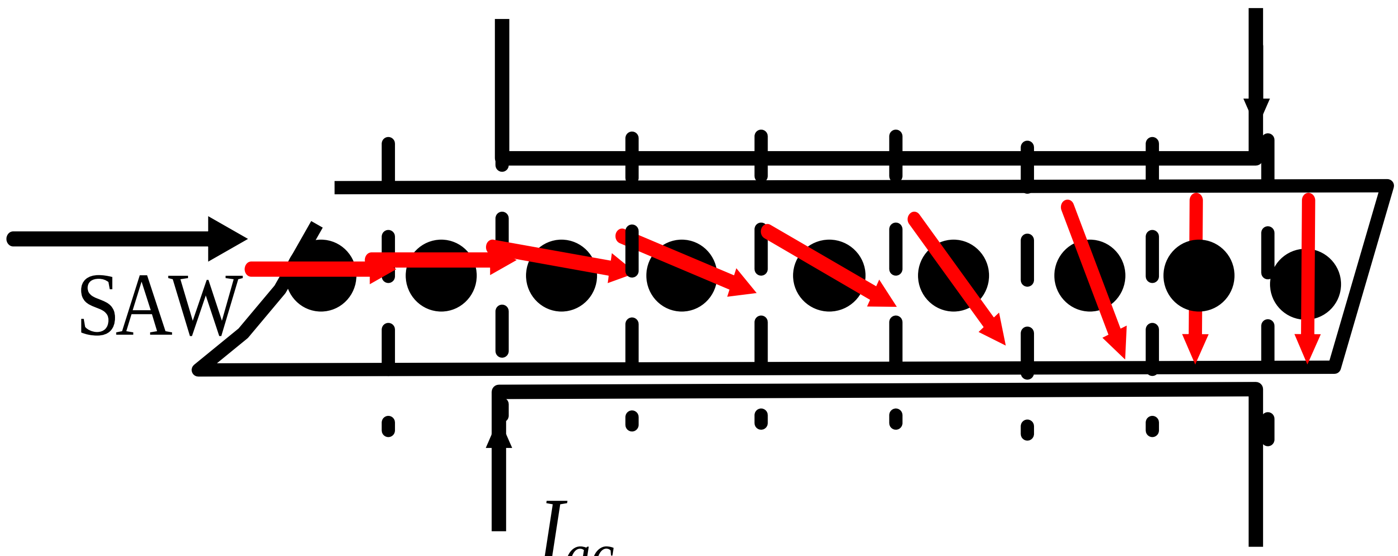
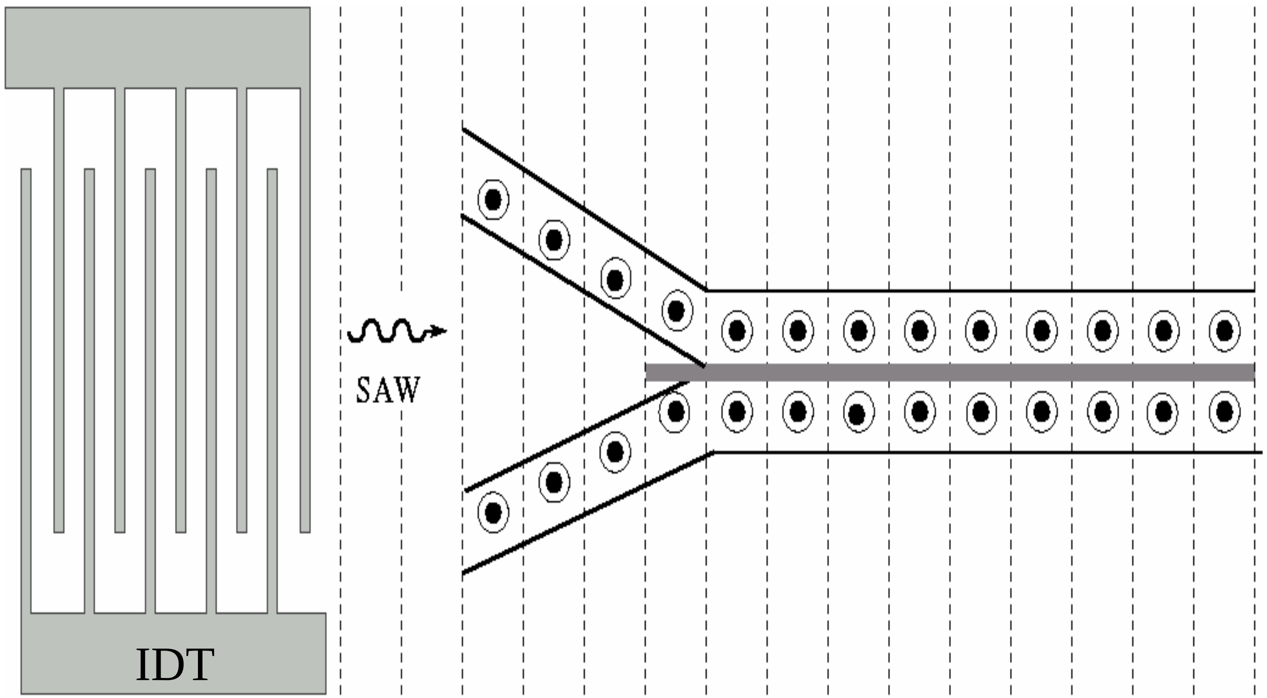
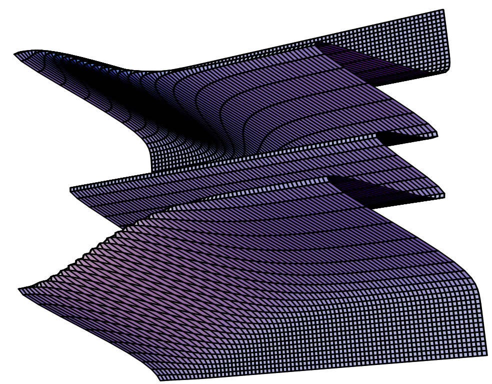


Fig.3

Schematic Diagram of Adjacent Channels



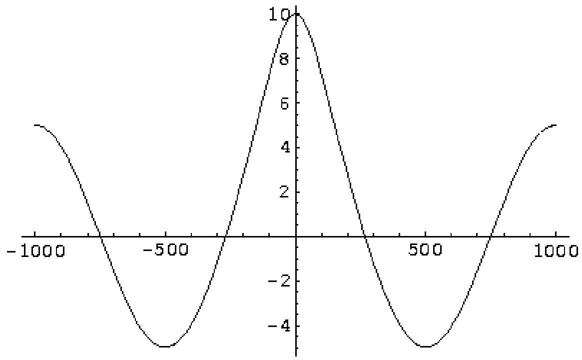


Theoretical Model

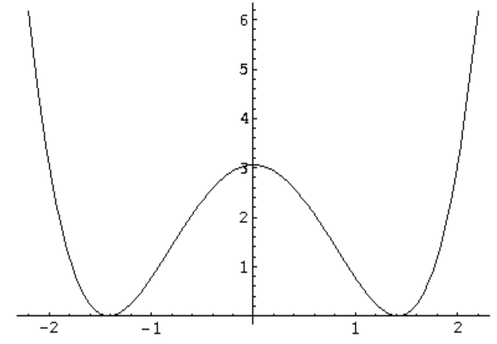
Model Hamiltonian

$$
\begin{aligned}
H(\mathbf{r}_1, \mathbf{r}_2, t) &= \sum_{i=1}^{2} \left(\frac{\mathbf{P}_i^2}{2m^*} + V_1(x_i, t) + V_i(y_i) \right) + H(\mathbf{r}_{12}) \\
V_1(x_i, t) &= \frac{V_0}{\cosh^2(x_i/\ell)} + V_{SAW} \cos(kx_i - \omega t) \\
V_2(y_i) &= \frac{m^* \Omega^2}{8a^2} \left(y_i^2 - a^2 \right)^2 \\
H(\mathbf{r}_{12}) &= \frac{e^2}{\varepsilon_s r_{12}}
\end{aligned}
$$

V(x,t) at t = 0.



V(y)



Calculation of the exchange interaction J(t)

Heitler-London Model

Singlet/Triplet States

$$|\Psi_\pm(\mathbf{r}_1,\mathbf{r}_2,t)\rangle \;=\; \frac{1}{\sqrt{2(1\pm S^2)}}\Big(|\varphi_+(\mathbf{r}_1,t)\varphi_-(\mathbf{r}_2,t)\rangle \pm |\varphi_-(\mathbf{r}_1,t)\varphi_+(\mathbf{r}_2,t)\rangle\Big)$$

Exchange energy

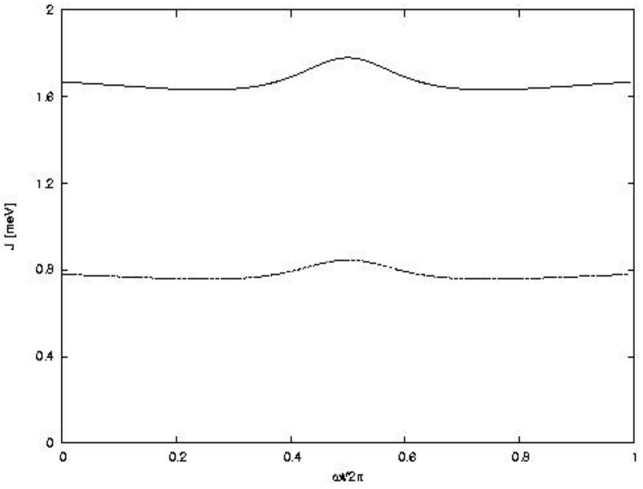
$$J(t) \;=\; \langle\Psi_-(\mathbf{r}_1,\mathbf{r}_2,t)|H|\Psi_-(\mathbf{r}_1,\mathbf{r}_2,t)\rangle - \langle\Psi_+(\mathbf{r}_1,\mathbf{r}_2,t)|H|\Psi_+(\mathbf{r}_1,\mathbf{r}_2,t)\rangle$$

Overlap integral

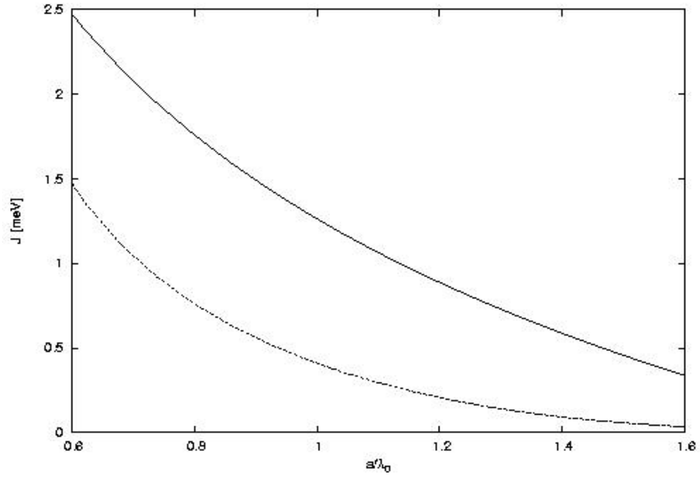
$$S \;=\; \langle\varphi_-(\mathbf{r})|\varphi_+(\mathbf{r})\rangle$$

Numerical evaluation of Exchange Energy

Comparison of Heitler-London Model with numerical evaluation of J(t) using Slater diterminant states.



J(t) vs. time over one SAW cycle



J(t) vs. inter-dot distance for t = T/4.

Quantum Gate Error due to Leakage

Instantaneous eigenkets:

$$H(t,\mathbf{r}_1,\mathbf{r_2})|u_\alpha(\mathbf{r}_1,\mathbf{r}_2 t)\rangle = E_\alpha(t)|u_\alpha(t,\mathbf{r}_1,\mathbf{r}_2)\rangle$$

Equation for coefficients:

$$\frac{\partial c_\alpha(t)}{\partial t} = \sum_{\beta\neq\alpha}\frac{c_\beta(t)}{E_\alpha(t)-E_\beta(t)}\langle u_\alpha|\frac{\partial H(t)}{\partial t}|u_\beta(t)\rangle e^{\frac{-i}{\hbar}\int_{t_0}^{t}d\tau\left(E_\beta(\tau)-E_\alpha(\tau)\right)} + \langle u_\alpha(t)|\frac{\partial u_\alpha(t)}{\partial t}\rangle$$

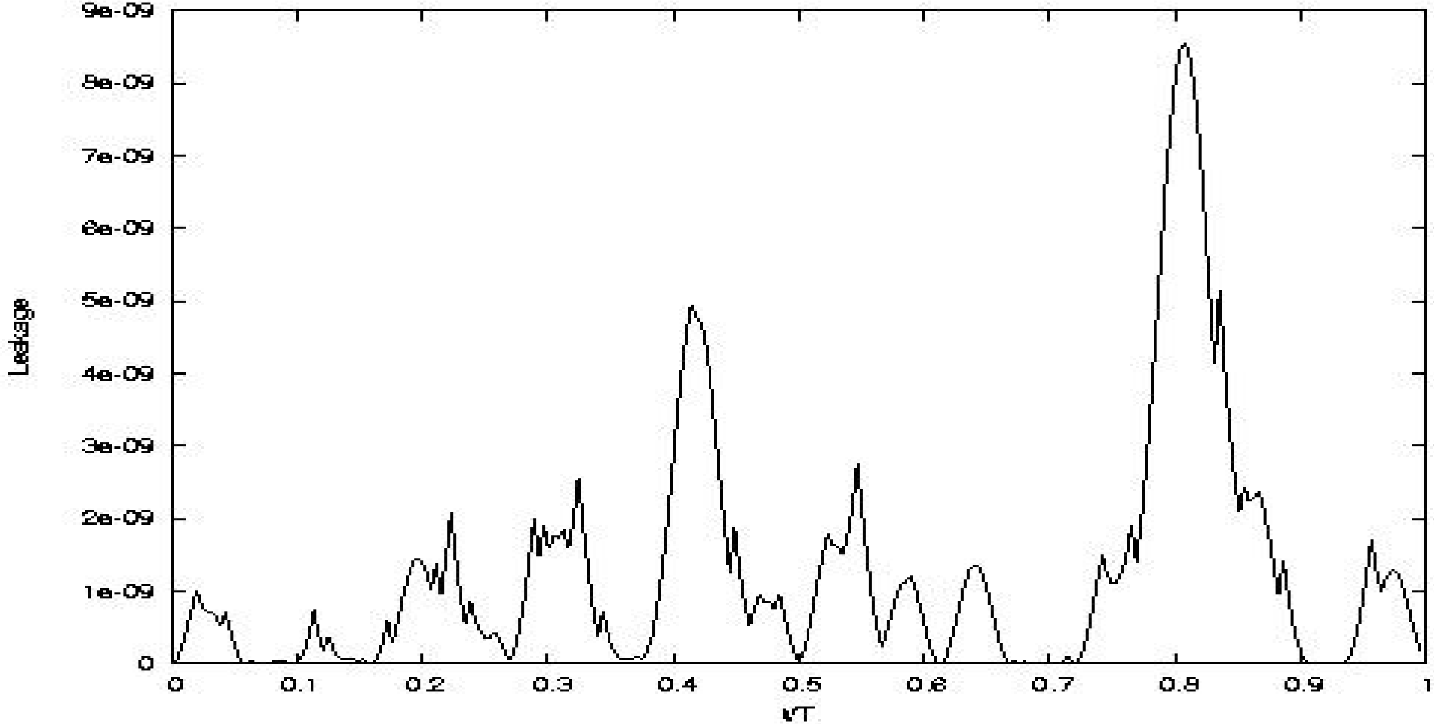
Initial condition:

$$c_\beta(0) = \delta_{\beta 0}$$

Leakage:

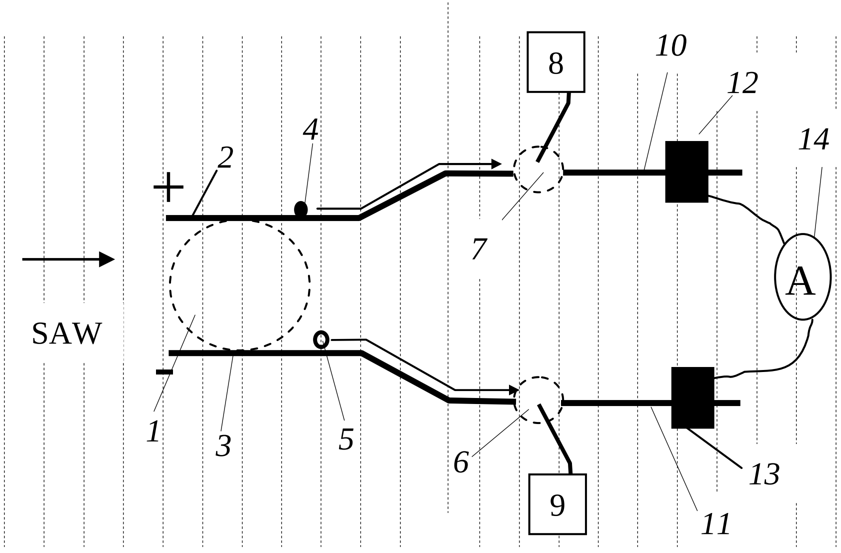
$$L(t) = 1 - |c_0(t)|^2$$

Oscillatory Behavior of the Leakage



Leakage vs. t;
T=SAW period

Acoustoelectric Single Photon Detector



Conclusions

- Calculated J(t) as the spins get transported by the SAW.
- J(t) > 0 indicating the entanglement remain is stable which is arequirement for QC and QIP
- The leakage to other states is calculated and is within the tolerance level for quantum error correction codes.
- Suitable for application to QC and QIP with a SAW cycle.
- Scalability.
- Possible applications of SAWs to a photon detector and photon source are currently being explored.

References

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