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Control of single-electron tunneling by surface acoustic waves

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We propose and use surface acoustic waves to control single-electron tunneling through an array of small tunnel junctions. The first experiments show that the wave traveling on the GaAs substrate couples to the islands of the array by modulating the potentials of their gates. We see cusps in the slope of the I-V curve at $f=290$ MHz around $I=\pm ef$. At 48 MHz and zero voltage biased to the ends we observe modulation of current by 3 pA around zero as a function of equal potential on the islands. Advantages of our method and problems, in particular the offset charge on GaAs, are discussed.

In this paper we present the idea and discuss experimental results on using surface acoustic waves (SAW's) as an alternative technique to control single-electron tunneling (SET) in arrays of very small tunnel junctions. For the past few years arrays of "Coulomb islands" have been investigated, in particular, as candidates for standards of electric current.[1,2] A few schemes to pass one electron per clock cycle (frequency f) through a one-dimensional (1D) array producing a current

$$I=ef \tag{1}$$

have been considered and realized experimentally. Three and five junction pumps[3–5] and a related device, a "turnstile,"[6] all have been successfully operated by coupling one or several islands of the chain capacitively to gate electrodes whose potentials are manipulated by rf voltages through external wiring.

The state-of-the-art circuits are accurate to about 1 ppm in transferring electrons.[5] One of the principal sources of error is cotunneling, which presents unwanted transfer of several coincident electrons in such a circuit. To suppress this it is advantageous to increase N, the number of junctions up to, say, 6–8. On the other hand, this leads to the complication of gate circuitry for $N-1$ islands and to a longer time for reliable transfer of an electron sequentially through all the array.[7,8] Quantitatively f should be much lower than $(NR_TC)^{-1}$. Here R_T is the tunnel resistance of a junction, and C is its capacitance. In practice, frequencies exceeding 100 MHz can hardly be used, and the currents ef in 1D arrays are limited to ~ 10 pA. To increase the speed, one could use a wave instead of clock pulses to move a train of electrons at a time.

The SAW on a piezoelectric substrate, in our case GaAs, is an electroacoustic surface wave that can be created by interdigital transducers.[9] The wavelength λ is determined by the distance between the fingers of the transducer. By the SAW one can create ac potentials on the islands of practically equal amplitude and well-defined phases simply by choosing the amplitude of the SAW and the ratio between λ and the distance between the gates in the SAW field without external leads. External dc gates to compensate for background charges may, however, be needed (see discussion below). Secondly, longer chains are as easy to operate, whereby end effects in the chain and cotunneling can be suppressed. Also, one can increase current by several parallel chains in a field of a wide enough SAW transducer.

Physically, the SAW penetrates within about λ into the substrate,[10] and due to the piezoelectric effect it causes charge polarization on the surface. With a conducting electrode on this substrate, the SAW affects as a set of fictitious charged capacitor plates beneath it and redistributes the charge on the electrode until a uniform total potential is achieved. If, however, we have electrodes separated by tunnel junctions, the potential of these islands varies in accordance with the phase and amplitude of the wave.

Figure 1(a) illustrates the principle and geometry of our measurement. A transducer, to the left, transmits the SAW. The gate antennas around the array in the center couple to the wave produced by rf voltage of the transmitter at its resonant frequency. The gate geometry together with the array is displayed on the schematics and on the scanning electron microscope image on the right. We report here mainly on measurements of two representative samples. Sample 1 consists of a chain of ten junctions 1 μm apart, operated at a frequency of $f=290$ MHz, with gate antennas separated by a distance $\lambda/2\simeq 5$ μm. Sample 2 has eight junctions 1 μm apart, operated at a frequency of $f=48$ MHz, with antennas at a distance $\lambda/4\simeq 15$ μm. The arms connecting the gate antennas and the island gates are 0.2 μm wide and they are 10–18 μm long.

Figure 1(b) shows an equivalent circuit for SAW coupling. The voltage of the SAW electric field, V_{SAW}, can be measured by another, identical SAW transducer on the opposite side of the sample. $V_{SAW}\simeq 14$ and 10 mV at 0-dBm transmitter level for samples 1 and 2, respectively. C_1 is the capacitance between the "SAW substrate" and the gate antenna. A rough estimate is given by $C_1\sim \epsilon\epsilon_0 A/\lambda$, where $\epsilon\simeq 13$ is the dielectric constant of GaAs and A is the area of the antenna. Here we assume that the charge induced by the SAW is concentrated in the substrate at a distance of λ from the Al conductor.[10] In sample 1 $A=100\times 2$ μm^2 and $\lambda=10$ μm; thus $C_1\simeq 2.5$ fF. Similarly, in sample 2 we have $A=100\times 7.5$ μm^2 and $\lambda=60$ μm; thus $C_1\simeq 1.6$ fF. $C_2\simeq 30$ aF is the usual gate capacitance to the island. Since no leads are connected to the gates we are unable to measure C_2 directly. Yet, $C_2\ll C_1$, and we may therefore neglect C_1. C_0 is the ground capacitance of an island, and its value is

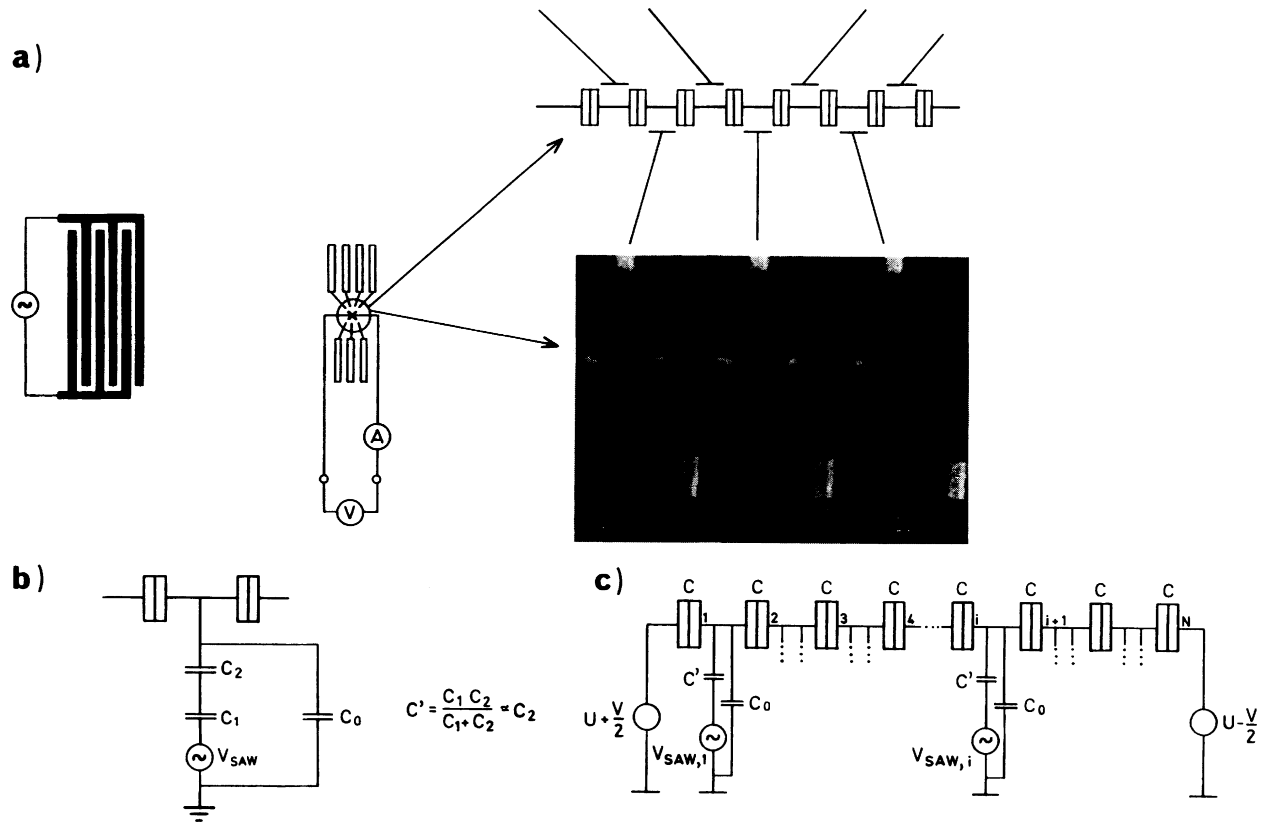

FIG. 1. Principle of the experiment. (a) Coupling surface acoustic wave to the tunnel junction array. (b) Equivalent circuit for SAW coupling. (c) A schematic representation of the tunnel junction array with symbols used. For further explanations see text.

<0.1 fF. Its magnitude was deduced from the periodicity of the Coulomb blockade vs U on the whole array as shown below. This also gave an indirect measurement of C_2, by comparing it to the periodicity in a sample without gates but which was otherwise similar. Figure 1(c) shows the scheme of the array, ac voltages, and the bias. The I-V characteristics could be measured by either symmetric $(+V/2,-V/2)$ or asymmetric $(V,0)$ bias to the ends, and also using an additional offset U.

We fabricate our samples by electron-beam lithography using a double-layer resist and angled evaporations of Al and oxidation in pure O_2 (99.998%) in between. Tunnel junctions and SAW transducers are exposed in the same lithography cycle. Measurements are carried out in a small dilution refrigerator in a transport Dewar with a minimum temperature below 50 mK. The measurements have been performed in the normal state of Al in a magnetic field of ~ 0.5 T.

The data of sample 1 are shown in Fig. 2. In 2(a) we see a typical I-V curve, in the absence of SAW's, at $T \simeq 50$ mK.

The Al electrodes couple to transmitted rf in at least two competing ways. Direct crosstalk has to be suppressed because it has a long wavelength (1–10 m), thus modulating all the islands in phase. SAW coupling can be identified since it has the characteristic resonance spectrum. Figure 2(b) demonstrates a fairly clean SAW coupling of sample 1; the slope dI/dV of the I-V curve at $V=0$ is displayed at a constant level of rf irradiation (-20 dBm) at the transmitter at frequencies around the resonance. The corresponding transmittance of the transducer (circles), measured independently by an opposite receiver, has a peak at the same frequency as the conductance curve with approximately the same width of $\Delta f/f \simeq N_f^{-1}$ for each of the peaks. Here $N_f=100$ is the number of fingers in the transmitter. If crosstalk dominates, dI/dV shows beating vs f with the interval determined by the distance between the transmitter and the array. In the present case, however, only a tiny rise of conductance ($\simeq 2\times 10^{-8}$ Ω^{-1}) is seen at off-resonance frequencies, which also indicates negligible heating of the sample by rf. The crosstalk was suppressed by careful shielding.

In Fig. 2(c) we plot dI/dV vs I of sample 1 at different values of V_{SAW}. Although no plateaus are seen in the I-V curve, the development of cusps with increasing V_{SAW} is obvious. The positions of $I=\pm ef \simeq 46$ pA are indicated by arrows. The effect of the SAW on SET in sample 1 is fairly weak. First, the frequency is high: the product $R_T C f$ is ~ 0.05, compared to the theoretical recommendation of $\sim 10^{-3}$ (see, e.g., Refs. 7 and 8) for a pumplike regime to be realized. Second, the degree of coherence of the autonomous process[11,12] in the array of only ten junctions is low to expect effective phase locking at $I=\pm ef$. Yet the latter coupling mechanism in the case of gates at $\lambda/2$ distance from each other altered the I-V curve noticeably.

In sample 2 the spacing between the gate antennas was $\lambda/4$, which yields a $\pi/2$ shift in the phase of rf voltages on the islands. Moreover, the lower frequency ($R_T C f \simeq 0.004$) is more preferable to obtain current $I=\pm ef$ even at $V=0$. According to our estimate this reduces the probability $p=\exp[\ln(N)-0.056/(fR_T C)]$ of missing the tunneling al-

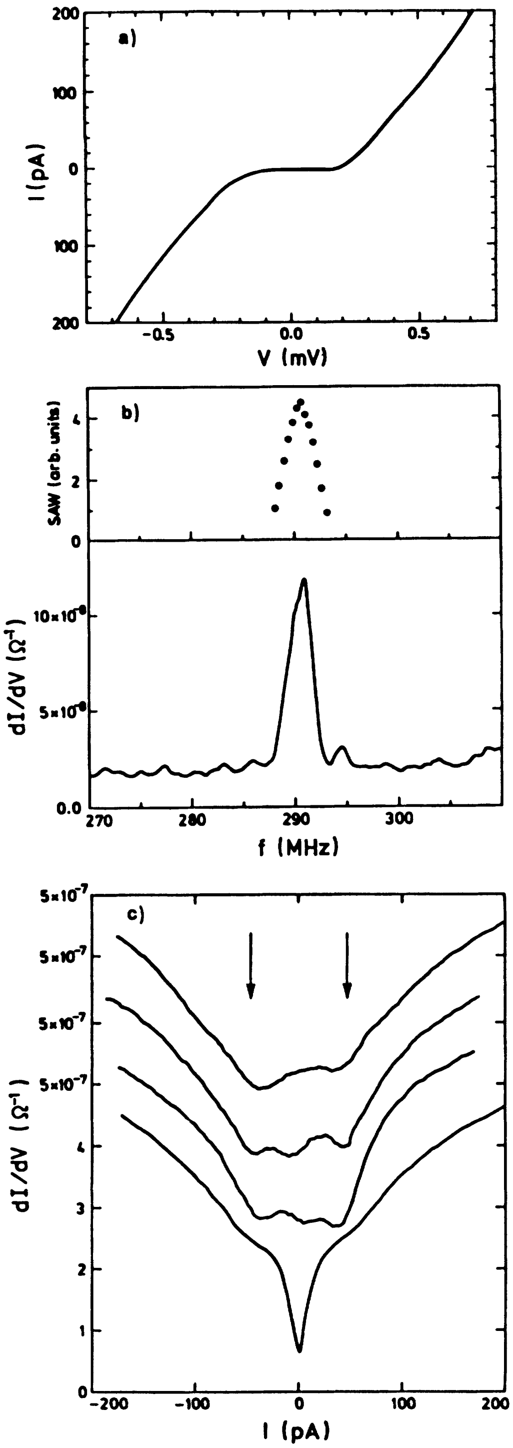

FIG. 2. Data of sample 1 with ten junctions in series ($C \simeq 0.7$ fF, $R_T \simeq 230$ kΩ) with nine SAW gates at $\lambda/2 = 5$ μm distance at $T \simeq 50$ mK. (a) Coulomb blockade in the absence of SAW's. (b) A spectrum of SAW coupling to the array. The open circles show the amplitude of the propagating wave around the resonance. The continuous line is the corresponding slope dI/dV of the I-V curve measured at $V=0$. (c) Conductance dI/dV vs I, at different levels of SAW's of -25, -22.5, -20, and -17.5 dBm from bottom to top, with a vertical offset of 10^{-7} Ω^{-1} for each curve. $I = \pm ef \simeq 46$ pA is indicated by arrows.

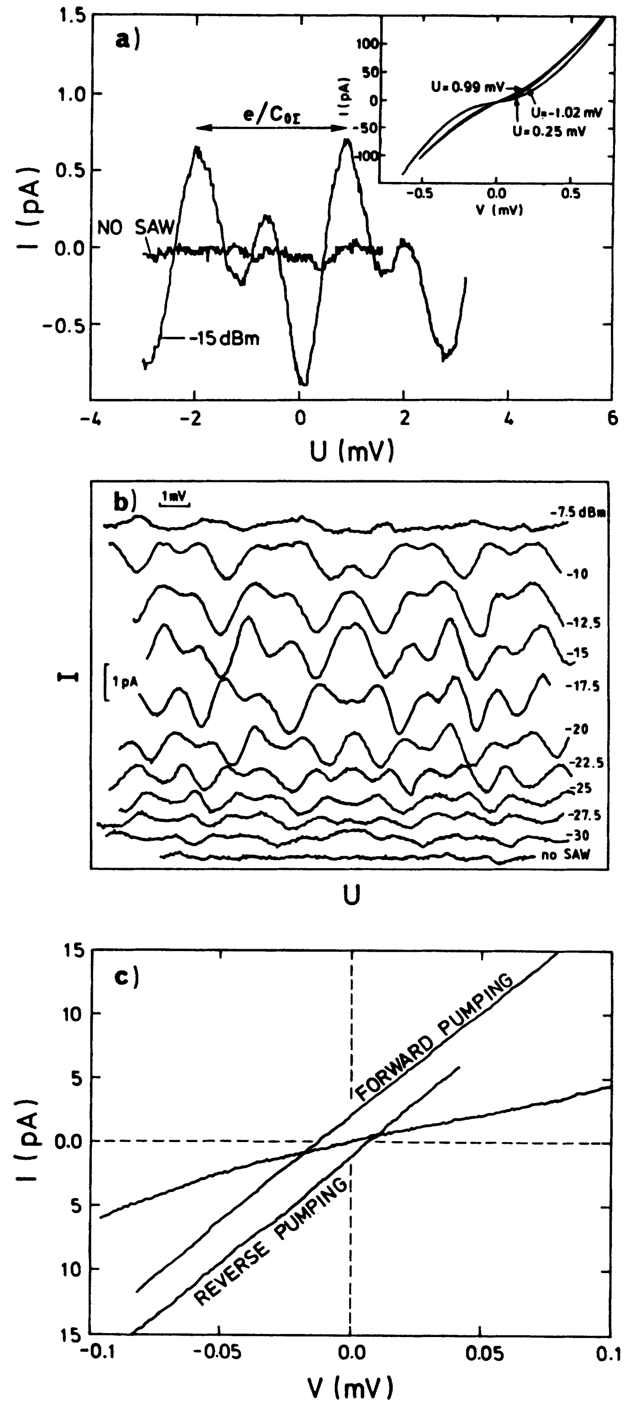

FIG. 3. Data of sample 2 ($C = 0.4$ fF, $R_T = 170$ kΩ) with seven SAW gates placed $\lambda/4 = 15$ μm apart. (a) Modulation of current at zero V as a function of bias U. The two lines correspond to no SAW's and -15-dBm SAW's at 48.1 MHz. The inset shows I-V curves at different values of U and at $V_{SAW} = 0$. (b) Modulation of current at different levels of SAW's. On the left and right halves of the figure, U is swept symmetrically up and down, respectively. (c) I-V curves in the range of small bias voltages in three different cases. The nearest to a flat one is without the SAW at $U = 0.25$ mV, and the two others are with -15-dBm SAW's at $U = +1.0$ mV on top and $U = -1.4$ mV below, respectively. In (a)–(c) $T \simeq 100$ mK.

ready down to $\sim 10^{-5}$. The physics of this can be understood as follows. Without excess charges in the chain, the distribution of electric potentials that the SAW induces onto the islands has a discrete sinusoidal wave form. When in addition to the SAW a uniform dc voltage U on the order of the amplitude of this sine is applied to every island, the voltage profile presents a number of only positive or negative bumps depending on the sign of U. These pulses travel in the same direction as SAW's, and if their amplitude is optimal (i.e., causes maximum polarization of about $\pm e$) they present ideal traps for single electrons or holes (vacancies). Therefore SAW's can transport a train of electrons (holes) through the array operating as an "Archimedean screw" for single charges. In this regime the performance of the system is like that of a pump. However, compared to the conventional N pump,[7,8] our pump contains at every instant $N/4$ electrons or holes (in our case two) instead of one, and could have in principle higher operation current.

The data of sample 2 have been collected in Fig. 3. In Fig. 3(a) we show the current through the array at $V=0$ when sweeping U. The measurement in the presence of -15-dBm SAW's exhibits variations of I with a total p-p difference of 1.7 pA almost symmetrically around the corresponding curve without SAW's. We consider this as an observation of the pumping of single electrons by surface acoustic waves. Note the existence of reverse pumping of holes as implied by the model above. The inset shows full I-V curves without SAW's at different values of U, further indicating that in this case modulation is present only at $V \neq 0$. The dependence of the modulation at $V=0$ on the SAW amplitude is shown in Fig. 3(b). One can clearly see $e/C_{0\Sigma}$ periodic dependence of I on U resembling that of a single-electron transistor (see, e.g., Ref. 1). Here $C_{0\Sigma} \simeq C_0 + C_2$. The relatively weak variation and the unexpected meanderlike shape likely originate because of uncontrollable offset charges. Every period corresponds to a uniform charging of all the islands with an extra elementary charge. At higher amplitudes heating may contribute to the diminishing of the effect.

In Fig. 3(c) we see corresponding I-V curves: one without the SAW ($U=0.25$ mV) and two at -15-dBm SAW's and $U=1.0$ and -1.4 mV above and below the first one, respectively. The vertical separation of the two extreme curves at $V=0$ is about 3.2 pA, which is approximately twice the modulation seen in Figs. 3(a) and 3(b). This difference comes from the setup of biasing: the whole array was biased through $R=10$ MΩ resistors at each end, whereby the modulation measurements of Figs. 3(a) and 3(b) represent nonvertical projections of 3(c).

The theoretical value of $I=\pm ef \simeq \pm 7.7$ pA for current modulation corresponds to the ideal operation of the system, which requires fair uniformity of the junction parameters and gate capacitances, but also smallness of stray background charge. Nonzero charges affect conditions for sequential tunneling in the array, and in combination with finite temperature reduce the probability of tunneling. Our numerical simulations indicate that the $I=\pm ef$ plateaus are not severely affected if we assume background charges Q_{0i} in the range $-0.2e < Q_{0i} < 0.2e$, whereas a fully random distribution $-0.5e < Q_{0i} < 0.5e$ washes out the effect even at $T=50$ mK.

The measured U modulation of current shows a drift of the pattern at $\sim 0.2e$/h accompanied by infrequent jumps a few times per hour. We observed similar varying background also in samples without gate antennas on GaAs, whereas our test samples on silicon exhibit better charge stability. Presently we are studying different substrate materials in this respect, and combination of dc gates with optimized SAW antennas.

In summary, we have demonstrated that surface acoustic waves can be used to modulate Coulomb blockade without serious heating of the sample. We have observed an anomaly in conductance of the array at $I=\pm ef$ by $f=290$ MHz SAW's. At $f=48$ MHz e periodic modulation of current at zero bias could be demonstrated with, surprisingly, alternating forward-reverse current pumping when sweeping U.

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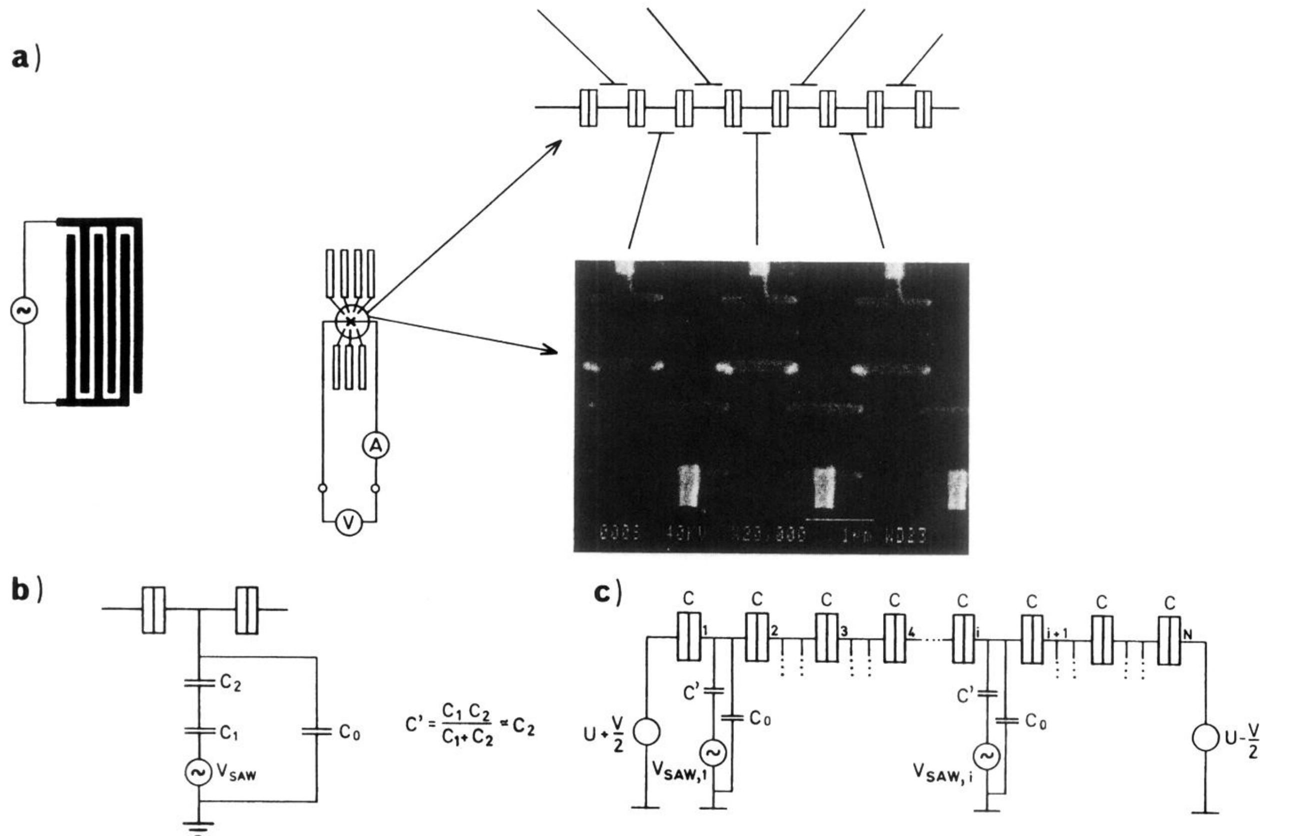

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