Current Switching and Modulation Based on Electron Interference in Electron Waveguides: A Zero Gap Electron Wave Coupler

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For the first time we fabricated electron waveguide devices analogous to optical guided wave devices. Specifically we made a zero gap electron wave coupler which demonstrated current switching and modulation based on electron interference in electron waveguides. Fabrication involves forming Schottky gate electrodes on the surface of a high mobility two dimensional electron gas sample. Under appropriate reverse bias, areas under gate electrodes are depleted of electrons and conduction from one side to the other can only occur through the narrow and short channels. These channels behave as electron waveguides if their dimensions and temperature of operation are appropriate. The gate geometry is such that two individual single mode waveguides at the input and output open up smoothly with the help of tapers to a double moded waveguide section in the center. The lithographic length and width of the wide waveguide section in the center are 3000Å and 9000Å respectively. The lithographic width of the input and output waveguides are about 4500Å. In the rest of the discussion we will assume that electrons propagate as coherent waves and their phases are preserved along the length of the device. Therefore, we can utilize the phase of the electrons to create electron interference resulting in spatial modulation of current. It is precisely this point that needs experimental verification to open up the possibility of new and novel electron devices based on electron waveguiding in analogy with optical waveguiding. We call this device zero gap electron wave coupler, because its principle of operation is identical to zero gap coupler in integrated optics. An electron wave incident from one of the single mode waveguides can emerge from either one of the output waveguides depending on the phase shift between the modes of the double moded waveguide. Therefore, it could be possible to achieve current switching with this device. The shape of the potential and the number of modes that exist in the wide center waveguide are controlled by the side gate voltages V_g. The coupler is driven by a constant current source of value 5.5 nA from the upper right port. The lower right port is left floating so the current in or out of this port is zero. We monitor the current coming out of the upper (direct current) and lower ports (coupled current) on the left. These so called direct and coupled currents versus V_g show an oscillatory behavior. One observes strong modulation of both currents at 0.1°K. This type of behavior is indicative of modal interference. The currents, however, do not modulate very strongly and the maximum modulation is about 40%. This is because the wide central waveguide always has more than two modes. As a result the number of modes that interfere in the central region is large. It is well known that interference of many waveguide modes creates a complicated interference pattern which never goes to zero. The situation gets worse as the number of modes interfering increases and in the limit of many modes interference effects become very vague. In this geometry, as Vg decreases, the number of modes of the wide waveguide at the center decrease and modal interference becomes stronger. But before the center guide gets sufficiently narrow, the input and output waveguides are pinched off because of geometrical considerations. It is observed that due to a slight asymmetry, lower left port is pinched off first, and all the current injected ends up in the upper left channel for V_g less than -2.7 V. As V_g gets larger the modal interference becomes weaker and eventually the areas under these side gates become no longer depleted and current partitioning is determined classically depending on the resistances of two current paths. Further evidence of modal behavior and interference can be gained by examining the temperature dependence of the current modulation. The same device is also characterized at three different temperatures before illumination. In this case current modulation is not as strong as the previous case (it is about 10%) at 0.1°K, but the same general features are again observed. Current modulation decreases significantly at 1°K and is completely lost at 4.2°K. This is because of small subband spacing in the wide central region. When the subband spacing in this region becomes comparable to thermal energy clear observation of individual modes are no longer possible, hence modal interference is no longer observed. On the other hand mobility varies very little over this temperature range and transport is ballistic for the mobility values (400.000 and 1.1×10^6 cm^2/V sec before and after illumination respectively). Therefore, if the observed modulation were due to something other than the modal interference it should have been observed at 4.2°K as well. Furthermore, presence of modes in the individual waveguides is experimentally observed as conductance quantization. The conductance quantization, hence clear observation of modes disappears at 4.2°K, further supporting the claim that current modulation exists only in the presence of one dimensional subbands and upon their interference. In conclusion, for the first time it is demonstrated that there is experimental evidence supporting the analogy between optical and electron waveguide devices. Therefore it may be possible to fabricate new and novel electron devices by exploiting this analogy.

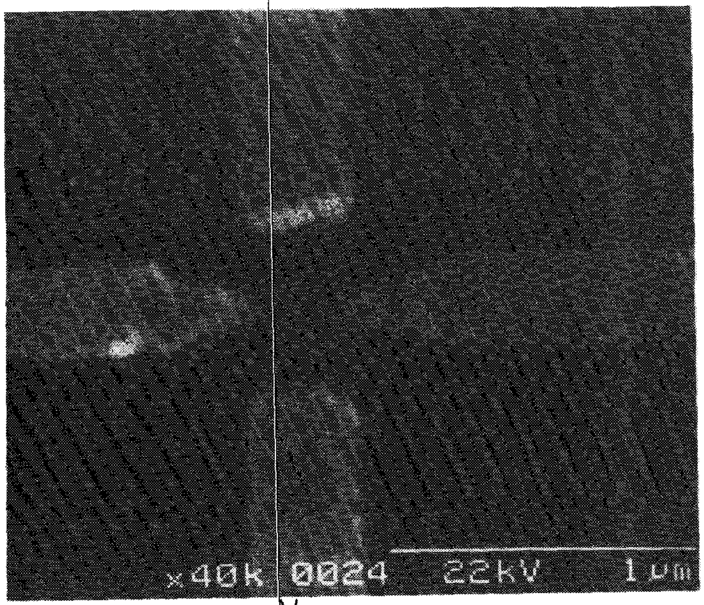
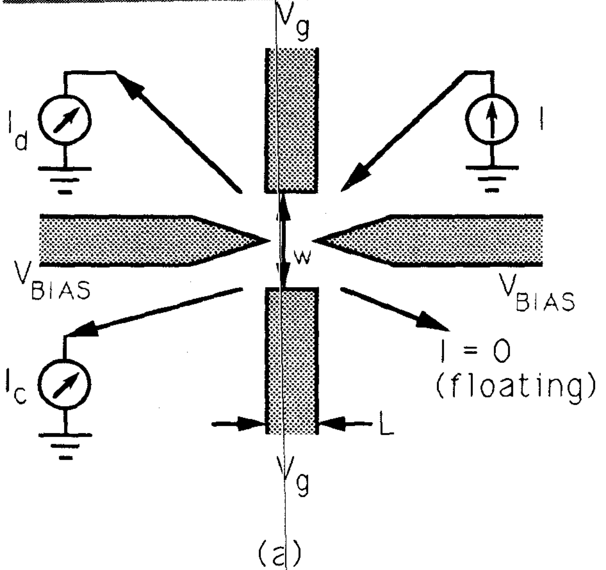


Figure 1. SEM picture of the gate electrode pattern of a fabricated zero gap electron wave coupler. White areas are the gate electrodes. Dark areas are the surface of the two dimensional electron gas sample.



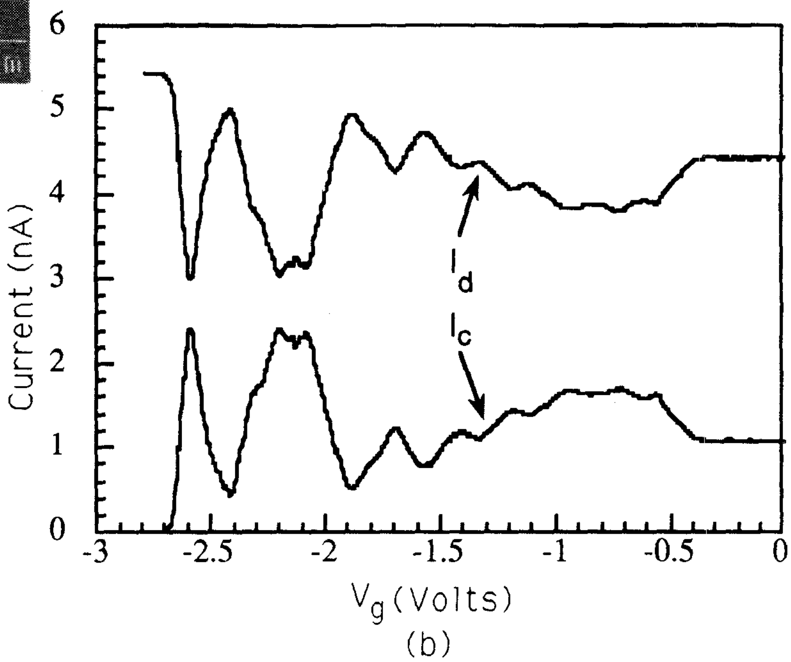


Figure 2. (a) Schematic showing the device geometry and bias conditions used in electrical characterization. In this case the separation between the tips of the input and output tapers, L, is 3000Å and the width of the wider region at the center, W, is 9000Å The bias on the center gates, V_{bias} , is -2.65 volts and temperature is about 100 milliKelvin. I is 5.5 nA. (b) Direct and coupled currents as a function of V_g. Electron mobility and sheet concentration are 1.1×10^6 cm^2 /V sec and 3×10^{11} cm^{-2} respectively (after illumination at 4.2K).

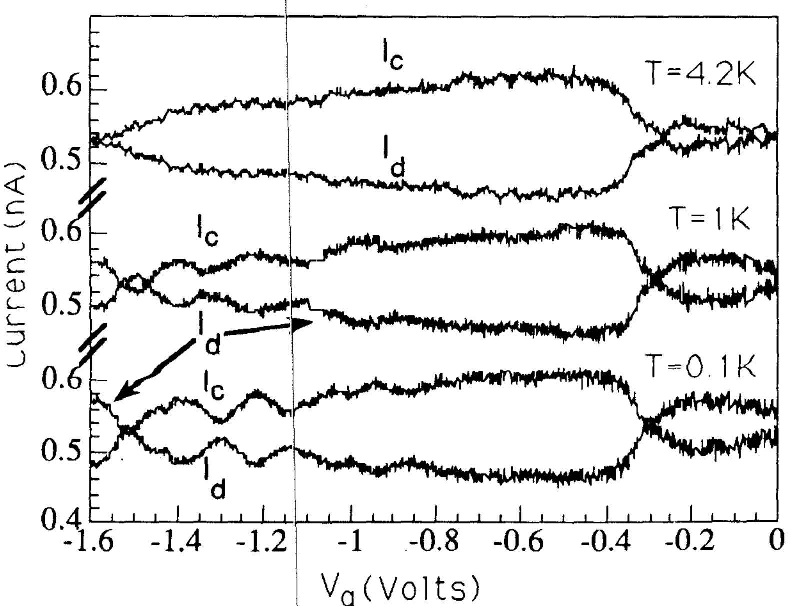


Figure 3. Direct and coupled currents from the same device described in figure 2. Currents measured at three different temperatures before the sample was illuminated. V_{bias}=-0.45V and I=1.06nA. Note that I_c and I_d cross over at 0.1K, and that the modal interference is suppressed at 4.2K.