The Electron Waveguide Y-Branch Switch: A Review and Arguments for its Use as a Base for Reversible Logic

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Utilization of the wave-like properties of the electron as a basis for functional devices to be used in logical circuitry has been discussed ever since the first demonstrations of quantized conductance in quantum point contacts (QPCs) [1, 2]. One rationale for such research is the predicted end-of-the-road of the scaling of MOSFETs and within this context electron waveguide devices have been considered potential successors of present-day MOSFETs [3]. Several types of electron waveguide devices have been proposed an discussed in the literature: electron waveguide directional couplers [4, 5, 6], quantum stub transistors [7, 8], Aharonov-Bohm-type transistors [9, 10], and the electron waveguide Y-branch switch [11]. Of these the Y-branch switch (YBS in the following) is especially interesting due to its gating response and required switch voltage. In contrast to the oscillatory response to changing gate potential of other electron waveguide device proposals the response to applied bias in the YBS is monotonic, which is desirable from a manufacturing point-of-view. Furthermore, the applied bias necessary to achieve switching when the electron waveguide Y-branch switch is operated in a single mode coherent regime is not thermally limited [12]. Combined, these two factors promise a device suitable for high-density packing through an expected tolerance to fabrication defects and very low power dissipation.

The electron waveguide Y-branch switch was first proposed by Palm and Thylén [11] and the original intention was an electron waveguide device shaped as a Y operating in the single mode coherent regime. Electrons are driven to propagate through the device by applying a bias between the stem and the branches of the Y. The envelope of the electron wave function propagates from the stem of the Y to either of the two arms, depending of the direction of an electric field applied across the branching region (Fig. 1). Thus it is a device that can be used as a basic building block in digital electronics. The switching properties of the YBS have been demonstrated in simulations [11, 13, 14] and experiments [15, 16, 17].

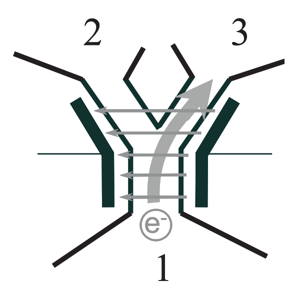

Figure 1: Schematics of the electron waveguide YBS. Electrons entering the stem from reservoir (1) are deflected to either of the two branches (2 or 3) depending on the direction of the electrical field across the junction applied by the voltages on the controlling gates.

As mentioned above, a key advantage of the YBS is that when operating in the single mode coherent regime the YBS lacks a thermal limit for switching. I.e. the change in applied gate bias required to change the state of the device, ΔV_S, is in the single mode coherent regime not thermally limited. It is instead limited by the electron transit time through the branching region of the YBS, τ_{tr} (as shown by

Palm *et. al.* [12]):

$$\Delta V_{S,YBS} \geq \frac{\hbar}{e\tau_{tr}}. \quad (1)$$

The switching voltage is thus fundamentally limited by the Heisenberg uncertainty time-energy relationship. The fact that the required switching voltage is not thermally limited can intuitively be understood from the point-of-view that the electrons need not be blocked by the gate voltage, but merely deflected. Sub-thermal switching has recently been experimentally demonstrated [18].

The electron transit time through the YBS is $\tau_{tr} = v_F/L_i$, where L_i is the interaction length, i.e. the physical length in which the electron is affected by the controlling gate bias. v_F is the Fermi velocity given by the sheet carrier concentration in the reservoirs, n_S:

$$v_F = \frac{\hbar}{em^*}\sqrt{2\pi n_S} \quad (2)$$

For a YBS manufactured by e.g. etching through a GaAs/AlGaAs 2DEG we can thus estimate the limiting value of $\Delta V_{S,YBS}$. With a typical carrier concentration of $4{\times}10^{15}\mathrm{m}^{-2}$ and an interaction length of approximately 200 nm, the limiting value of the switching voltage is of the order of 1 mV. By careful design and choice of material system a significantly lower value should be possible to be obtained. By contrast, the thermally limited switching voltage of a FET, which can be approximated to be [12] $\Delta V_{S,FET} = \log(10)k_B T/e$, is more than a factor 50 higher at room temperature.

Mode evolution of the electron wave function as originally proposed is not the only mode of operation for the YBS. Other modes of operation exist as well. In the single mode coherent regime, the possibility of self-gating operation, i.e. switching the YBS without the use of gates but by the use of space charge effects, has been suggested [19] (yet remains to be experimentally verified). The YBS can also be operated in a nonlinear multi mode regime, with quite different operating characteristics compared to the linear single mode regime. In this multi mode regime, 'ballistic switching' [20] have been demonstrated even at room temperature [21, 22, 23]. It should be mentioned that as the operating principle of the YBS in the ballistic switching regime is principally different to the coherent switching, power consumption that is not thermally limited by can not be expected.

Early considerations of the YBS did not consider the influences of space charge on the switching, however Wesström suggested [19] that the internal charge distribution of the device may influence the switching characteristics of the YBS more than the applied gate bias. Later, simulations [24] partially supported this conclusion, showing that space charge effects can severely disrupt the desired response to the applied gate bias. The simulations in did however also show that while operating the YBS with low currents, i.e. using a low supply voltage, the desired gate bias response is retained. The drawback of operating at low currents is low speed of circuits based on the device as there exists a trade-off between speed and current. However, as we can expect that future computational devices will rely more on massive parallelism rather than high speed, this should not be a drawback for the YBS. Furthermore, we notice from condition (1) that a longer cycle time τ_c will reduce the necessary switching voltage since by definition $\tau_c > \tau_{tr}$ needs to be fulfilled.

In terms of circuit design it has been shown, by simulations, that important factors such as fan-out the and the ability to cascade the YBSs are possible [12]. An important point for circuit design based on the YBS is that the low-voltage limit on switching of the YBS as expressed in condition (1) only requires single mode coherent transport in the branching region. This greatly simplifies design of circuitry based on the YBS as it is preferable to have regions between the YBSs where the electrons can thermalize. This to avoid complicated patterns of reflection and interference in the gates making them more robust to fabrication defects. Thus complex circuits are manufacturable as long as discrete YBSs can be fabricated. Such have already been demonstrated in the InGaAs/InP [15], GaAs/AlGaAs [16, 17] and InAs/AlSb [25] material systems, using various gate technologies.

In the devices demonstrated so far the gate efficiency is not very high. The necessary switching voltages are still far above the theoretical limit, thus drowning the power dissipation from information erasure. At present the best results still requires switching voltages of the order of 0.5 V [17, 26], which should be compared to the somewhat conservative limit for a GaAs/AlGaAs YBS of comparable size of approximately 1 mV calculated above. Nevertheless, higher gate efficiency can be expected by improved device processing methods, the gate technology used in [17] seems e.g. very promising in this respect. The theoretical limit of achievable gate efficiency is presently not known, however simulations have indicated that screening by space charge inside the YBS may limit the gate efficiency to about 10% [24]. Current devices also need to operate at liquid Helium temperatures to be able to display coherent phenomena (ballistic switching on the other hand is, as mentioned above, clearly visible at room temperature). Most practical applications on the other hand, excluding e.g. high-end supercomputers for weather simulations, will require devices to operate at elevated temperatures. There is however nothing that in principle prohibits coherent transport at room temperature as fabrication techniques improve. Partial ballistic transport have already been observed at room temperature [30, 31].

Using the YBS as a base for conventional logic circuitry was considered early on [32] and have also been demonstrated experimentally [33]. It is however questionable that any electron waveguide device will become a viable successor technology to MOSFETs if the focus remain on mimicking FET-characteristics and using them as a base for convectional logic. It would be more beneficial to consider using the YBS as a base for reversible logic (for more information on the field of reversible computing turn to e.g. work by Bennet [27], Toffoli and Fredkin [28, 29] and descendant literature).

For a device with capacitive inputs such as a FET or the

YBS, the energy dissipation when switching is

$$E_{sw} = C\Delta V_S^2, \quad (3)$$

where C is the capacitance. If we estimate the gate capacitance of a typical YBS in GaAs/AlGaAs to 0.1 fF and insert this together with the limiting switching voltage calculated above $\Delta V_{S,YBS} = 1$ mV into Eq. (3), we find the energy dissipated for one switching operation to be approximately 0.6 meV. This is more than an order of magnitude smaller than the minimum energy cost of information erasure; at room temperature $kT \ln 2$ is approximately 18 meV. The numbers used are deliberately conservatively chosen, by careful device design the energy cost for a switching operation could be made even smaller. Hence we can expect the cost of information erasure to be a major contributor to the total power dissipation in logic circuits based on (ideal) YBSs. The conclusion must thus be that it would be highly beneficial to use logically reversible gates that avoids information erasure rather than conventional gates when constructing logic based on the YBS.

Reversible logic based on the YBS has recently been proposed [34] in the form of a controlled-exchange (Fredkin) gate. Such a gate is manufacturable today. As techniques for fabrication of nanoscale electronic devices improve we can anticipate that information erasure will become a dominant mechanism for power dissipation in logic circuits based on electron waveguide Y-branch switches. While it should be noted that a number of important issues still needs to be addressed, e.g. the issue of timing, it seems quite clear that the reversible logic circuits based on the YBS have a potential to be a viable alternative to present-day transistor technology when this will reach its energy efficiency limit.

The review of the YBS presented in this paper is, as the reader already have noticed, brief and is only intended as an introduction. The reference list should however prove valuable as a starting point for the interested reader. It should also be mentioned that potential reversible logic circuits based on the YBS has been the reason for writing the review. Thus work done on the YBS operating in other regimes than the single mode coherent regime have not been given attention proportional to the amount of work published.

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