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Novel Pulse-Mode Neural Circuits Based on an AlGaAs-GaAs Multi-Quantum Well Diode

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Abstract

This approach to hardware implementation of artificial, electronic pulse-mode neural circuits is based on a new compound semiconductor device called a Multi-Quantum Well Injection Mode Diode (MQW-IMD) [1,2]. A trigger circuit consisting of the MQW-IMD and RC load switches periodically between a low conductance off state and high conductance on state generating a pulse mode output. For interneuron circuit, the input can be configured to accept pulsed inputs from multiple sources to replicate the operation of the interneuron, performing temporal integration, synaptic weighting (excitatory and inhibitory) and signal integration over multiple inputs analogous to that of the dendritic structure of the biological neuron.

I. INTRODUCTION

In this work our approach to the hardware implementation of neural network has been to devise a methodology using a custom designed device. This is in contrast to most approaches utilizing conventional transistors and circuits. In particular, the approach based on the MQW-IMD taken here has been to devise relatively simple circuit equivalent to the neuron that can be fabricated in a compact form and interconnected to form simple artificial neural circuits.

Described in the following section is a novel heterojunction device called a Multi-Quantum Well Injection Mode Device (MQW-IMD) whose operation has recently been demonstrated [1,2]. Discussed is the device's structure, its operation and the origins of its unusual S-type current-voltage characteristic. In the subsequent section the device's use and operation in simple circuits exhibiting neural-like behavior is described including trigger circuit, excitatory and inhibitory neural circuit and interneuron circuits with multiple inputs and outputs accepting pulse signal.

II. DEVICE OPERATION

The device consists of a multi-quantum well structure of alternating n^+ doped wells and undoped barrier layers placed between an anode and cathode as seen in Figure 1 (a). At low voltages (less than the threshold voltage V_{Th}), conduction is limited by thermionic injection of carriers at the anode and cathode so that the current level is extremely small and the device is in low conductance state as seen in Figure 1 (b). When a bias greater than the threshold voltage is applied, the electric field in the barrier layers becomes larger than the critical field needed to produce impact ionization of electrons from the wells. As the electrons are ejected from the wells, they leave behind a positive space charge so that the electric field at the cathode is enhanced thereby increasing electron injection. Since this process is a positive feedback one, the device rapidly switches to a high conductance state (Figure 1 (c)) characterized by an enlarged electric field at the cathode as seen in Figure 1 (b). As the bias is reduced, the device remains in the high conductance state until the cathode field drops below the critical field needed to produce impact ionization at the holding voltage V_H.

Figure 2 (a) shows a scope trace of the current-voltage characteristic for the device implemented in the AlGaAs/GaAs materials system. During the return sweep, the measured current shows a diode-like characteristic. To clarify the bistable operation of the device, Figure 2 (b) shows a single sweep measurement of the characteristic. The physics of the device's operation has been examined and described elsewhere [1- 4].

III. MQW-IMD-BASED NEURAL CIRCUITS

Based on the unusual s-shaped current-voltage characteristics of the MQW-IMD device, pulse-mode neural-like circuits can be configured. An essential functional characteristic of neurons that is replicated here with an elementary MQW-IMD-based circuit called a trigger circuit (shown in Figure 3 (a)) is the generation of an output pulse train of uniformly shaped and sized pulses where the frequency and duration of the pulsed output is a function of the input signal. The circuit generates a sequence of output pulses of nearly uniformly shaped peaks as shown in Figure 3 (b) with the pulse frequency dependent on the MQW-IMD device structure and on the applied dc input bias. The origin of the pulsed operation of the circuit is schematically illustrated in Figure 3 (c). Initially, the applied bias falls nearly totally across the MQW-IMD as only a very small leakage current flows while the device is in its low conductance state and so the output voltage is negligible. As a result of this positive feedback mechanism of the device, the current rises dramatically as the device switches to the high conductance mode. Correspondingly, the output voltage rises as the load capacitor charges up and the applied bias across the MQW-IMD drops nearly shutting off the current and forcing the device back into the low conductance state. Once the MQW-IMD shuts off, the output voltage decays with the time constant of the RC load and the bias across the device begins to rise and the process starts again.

This electronic trigger circuit exhibits several key characteristics of the neuron's trigger zone or axon hillock. First, it exhibits a threshold behavior. This is analogous to the behavior of the trigger zone of the neuron before action potential pulses are generated [5]. Second, for the input bias above the threshold, the MQW-IMD-based trigger circuit generates output pulses of nearly uniform shape and with an amplitude (hundreds of millivolts) and frequency (kHz) comparable to that of the neuron which is similar to the operation of the biological neuron [5]. Third, the output pulse frequency varies in a sigmoidal fashion with size of the input bias signal shown in Figure 4, which is similar to the dependence of the frequency of action potential pulse generation on the average membrane potential in the trigger zone for the biological neuron [5]. Fourth and finally, for the MQW-IMD-based trigger circuit, the output pulse frequency will saturate at sufficiently large input bias due to the finite time required to discharge the output load capacitance and for the positive charge in the wells to be neutralized.

For interneuron communication, a circuit can be configured as seen in Figure 5 (a) where in this case the diode is used to ensure that each incoming pulse deposits an amount of charge on the input integrating capacitor which corresponds to the neuron's membrane capacitance [4]. The amount of charge deposited is dependent on the size of the input coupling capacitor C_i and on the biasing of the diode (I_b) as determined by R_{dd} and V_{dd} and as shown in equation (1) below

$$f_o = \frac{C_i V_p}{C_L[V_{Th} - V_H]} f_i + \frac{I_b - \frac{V_{IN}}{R_{IN}}}{C_L[V_{Th} - V_H]} \qquad (1)$$

where V_{IN} is the time average input voltage to the MQW-IMD. In that the prefactor relating the output pulse frequency to the input frequency is a function of the input coupling capacitance C_i, the synaptic weight accorded a given size input signal corresponds to the efficiency of coupling input charge onto the input integrating capacitor C_{IN} and can be preselected by the choice of C_i. Shown in Figure 5 (b) is the measured output pulse frequency versus the input pulse frequency for various input coupling capacitances. As can be seen, there is a linear relationship with the slop a function of the input coupling capacitor. This characteristics behavior is analogous to the synaptic weighting function in biological neural systems [6].

It is also interesting to note that due to the integrating nature of the input capacitor C_{IN}, this electronic neural-like circuit performs temporal integration over multiple input pulses provided the $R_{IN}.C_{IN}$ time constant for the input is long compared to the time between input pulses. That is, there is a short term memory capability whereby even though individual input pulses are not sufficient to produce output pulses, their effects can be summed over a short period of time so that there collective effect is to produce a pulsed output. This is analogous to the temporal summation of subthreshold pulses seen in biological neurons [5].

Inhibitory input signals can be recognized with a slightly different circuit configuration as seen in Figure 6 (a). In this case each incoming pulse acts to remove charge from C_{IN} and so reduce the input potential momentarily inhibiting the firing of the MQW-IMD. In addition, more than one input each with a different synaptic weight and with both excitatory and inhibitory inputs can be constructed at the circuit's input to achieve summation over multiple inputs with individually weighted values as seen in Figure 6 (b) where the structure is comparable with that of the biological neuron. Mathematically, the operation of this electronic neural-like circuit shown in Figure 6 (b) can be described by

$$f_o = \frac{1}{C_L[V_{Th} - V_{off}]} \left[\sum_{n=1}^{N} [C_{jn} V_{pn} f_{jn}] - \sum_{m=1}^{M} [C_{jm} V_{pm} f_{jm}] \right] + \frac{\sum_{n=1}^{M+N} I_{bn} - \frac{V_{IN}}{R_{IN}}}{C_L[V_{Th} - V_{off}]} \qquad (2)$$

where the first sum is over the excitatory and the second over the inhibitory inputs.

IV. CONCLUSION

Based on the MQW-IMD's unusual s-type switching characteristics between low and high conductance states, the device can be used to construct simple electronic neural-like circuits with a number of characteristics similar to those of the biological neuron. A simple trigger circuit replicates the operation of the axon hillock generating a pulse-train output with a frequency corresponding to the input (mean membrane) potential. In combination with the conventional devices, pulse-mode inputs can be accepted with either excitatory or inhibitory characters and weighted. The input can also be configured with multiple inputs which are analogous to the dendritic tree-like structure of the neuron accumulating and weighting multiple input signals.

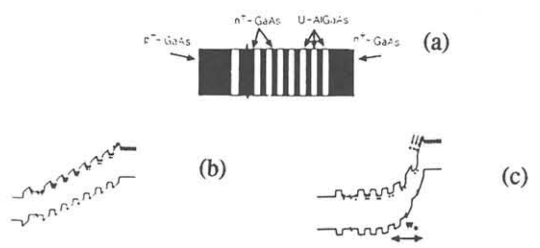

Figure 1. The structure of MQW-IMD (a) and energy band diagram in low (b) and in the high conductance state (c).

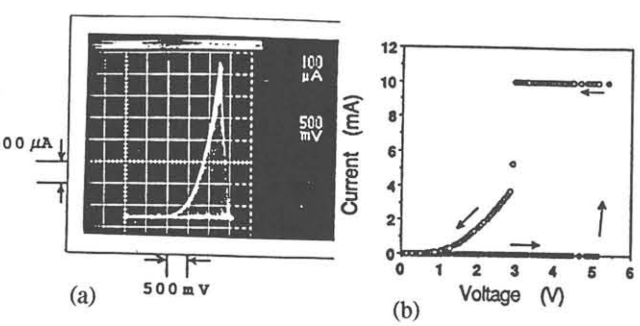

Figure 2. Measured current-voltage characteristic for MQW-IMD: (a) scope trace and (b) single sweep.

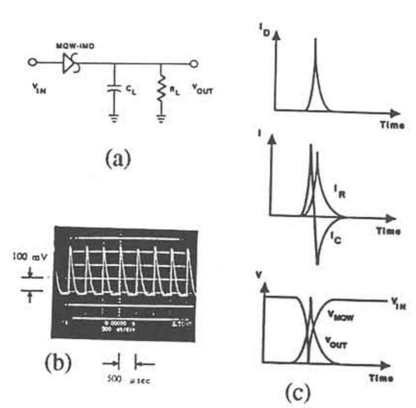

Figure 3. Simple trigger circuit (a) generating a pulse-train output (b) for a dc input bias. Part (c) shows the origin of the pulse generation.

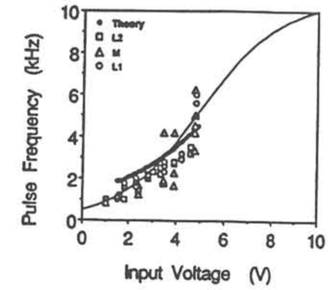

Figure 4. Experimental and theoretical pulse frequency vs. dc bias for MQW-IMD for the trigger circuit and sigmoidal behavior of frequency dependence.

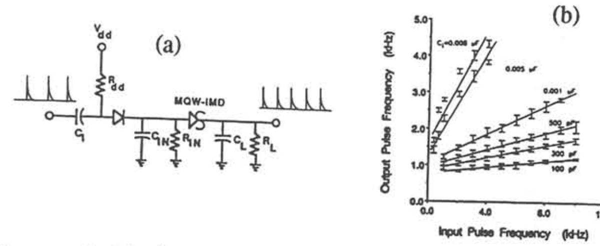

Figure 5. Excitatory neural circuit using MQW-IMD (a) and (b) experimental output frequency vs. input frequency for various input coupling capacitances.

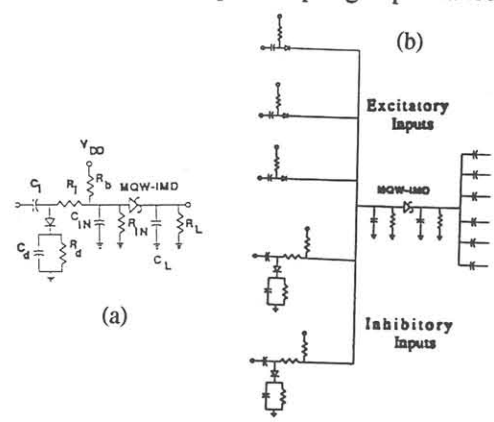

Figure 6. Inhibitory neural circuit (a) and multi-input circuit configuration (b).

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