Turn-on circuits based on standard CMOS technology for active RFID labels

David Hall*[a], Damith C. Ranasinghe[a], Behnam Jamali[a],Peter H. Cole[a]
[a]School of Electrical & Electronic Engineering, Univ. of Adelaide, SA, Australia 5005

ABSTRACT

The evolution of RFID Systems has lead to the development of a class hierarchy in which the battery powered labels are a set of higher class labels referred to as active labels. The battery powering active transponders must last for an acceptable time, so the electronics of the label must have very low current consumption in order to prolong the life of the battery. However due to circuit complexity or the desired operating range the electronics may drain the battery more rapidly than desired but use of a turn-on circuit allows the battery to be connected only when communication is needed, thus lengthening the life of the battery.

Two solutions available for the development of a turn on circuit use resonance in a label rectification circuit to provide a high sensitivity result. This paper presents the results of experiments conducted to evaluate resonance in a label rectification circuit and the designs of fully integrable turn-on circuits. We have also presented test results showing a successful practical implementation of one of the turn on circuit designs.

Keywords: Schottky barrier diode, turn-on, RFID, active labels

1. INTRODUCTION

A simple illustration of the concept of a Radio Frequency Identification (RFID) system is provided in Figure 1. Here a transmitter of interrogation signals which is contained within an interrogator communicates via electromagnetic waves with an electronically coded label to elicit from the label a reply signal containing useful data characteristic of the object to which the label is attached. The reply signal is detected by a receiver in the interrogator and made available to a control system.

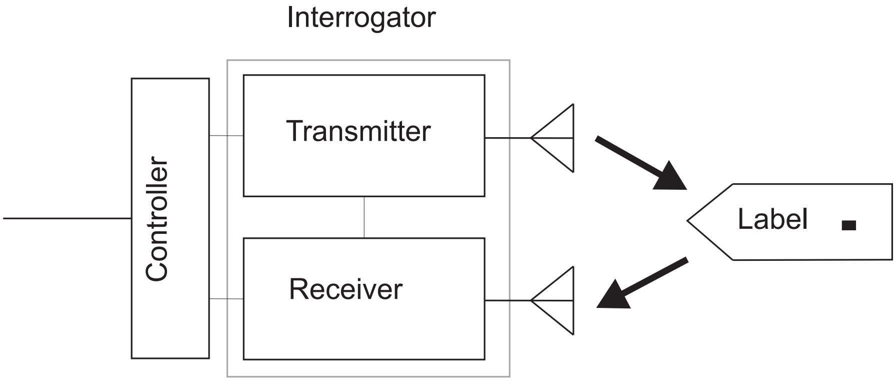

Figure 1: Illustration of an RFID system.

There is a wide range of operating principles for such a system [1,3]. The operating principle and operating frequency are driven principally by the application of the labelling system and the constraints provided by electromagnetic compatibility regulations, environmental noise, and the ability of fields to permeate a scanned region of space or to penetrate intervening materials. Applications are found in reliable and secure data collection, object or personal identification and authentication, and the detection of location of scanned objects [2].

* dhall@eleceng.adelaide.edu.au; phone +61(8) 8303 4119

In a primary category of passive systems the most common operating principle is that of RF backscatter [2] in which a powering signal or communication carrier supplies power or command signals via an HF or UHF link. However the circuits within the label operate at RF or lower, and reply via sidebands generated by modulation, whin the label, or part of the powering carrier. This approach combines the benefits of relatively good propagation of signals at HF and UHF and low power of operations of microcircuits at RF or lower. Powering at UHF is employed when a longer interrogation range (several meters) is required, and HF powering is employed when electromagnetic fields which exhibit good material penetration and sharp spatial field confinement are required or very system implementation cost is desired.

In the category of active labels the most common objective is to obtain a long range. Some active labels are battery-assisted backscatter labels while other types of active labels may not use backscatter but instead use a battery for powering and transmitting requirements (independent reply generating labels). This paper examines and presents practicable solutions to extending the lifetime of such active labels by using turn-on circuits to prolong the lifetime of the battery and hence the lifetime of the label. The lifetime of a label is also an important consideration in the use of high performance long lifetime theft detection labels.

2. TURN ON CIRCUITS

The primary focus of this paper is on active RFID labels that are equipped with a power source (such as a paper battery). The interrogation of active RFID labels will inevitably involve the development of a mechanism for turning on the labels as power conservation is an important factor that requires the labels to be turned off when not being interrogated. This situation will also be true for active sensors and sensor networks.

The turn-on requirements of active backscatter labels are different from independent reply generating labels. An active backscattering label will modulate the powering carrier or a sub-carrier to establish a communication link with the reader while using the battery to power the logic circuits of the label. However an active label that uses an independent source of power for generating a reply to a reader uses the on-board battery to power the transmitter of the label. This distinction is more apparent in the range of operation of the label. A reply from a backscattering label is very weak, and under a RFID system operating under the US regulations for the ISM (Industrial, Scientific and Medical) band of 902-926 MHz (allowed transmit power in this band is 4W EIRP), a backscattered reply can only be correctly decoded in the range of tens of meters. Thus a turn-on circuit need only work within the range of tens of meters. However an active label with an independent source of power for reply generation will work in the range of several hundred meters. Thus a turn-on circuit for this situation will need to be operated at a greater distance. The turn-on circuit presented in the paper is for active backscattering labels and for active labels with an independent source of power for reply generation. The following sections of the paper will focus on the practical evaluation of the concepts and a discussion of a detailed implementation and of test results of the circuit.

2.1 Concept

The practical options for turn-on circuits are two fold:

1. Rectifier circuits that can produce from an illuminating RF field a rectified voltage of the order of 1V that can turn a CMOS transistor from fully off to fully on; or

2. Rectifier circuits that can produce from an illuminating RF field a rectified voltage of the order of 5mV which when compared to an internal reference voltage can be used to trigger a transistor from fully off to fully on state.

For the production of a rectified output even to an open circuit load, a rectifying diode must experience across the junction capacitance a voltage of the order of or greater than the rectified output, and hence a minimum of reactive power must flow into and out of the junction capacitance. To service that reactive power, a resonant rectifier must be provided and the power lost in that resonant rectifier must be provided by the available source power from the antenna. Circuits of this latter type are described in the following Section of this paper.

2.2 Evaluating the concept

A label antenna, that in this application is preferably inductive, and the rectifying circuit that is intended to produce a rectifying voltage used for circuit turn-on, can be modelled as indicated in Figure 2. Here R_r represents the antenna radiation resistance, X_s represents the antenna reactance, X_l represents the reactance of the diode capacitance, X_B is the reactance of the reservoir capacitor that also serves as an RF bypass, R_l represents the loss in bringing reactive power into and out of the diode junction capacitance, and R_a is the ohmic loss contribution from the antenna.

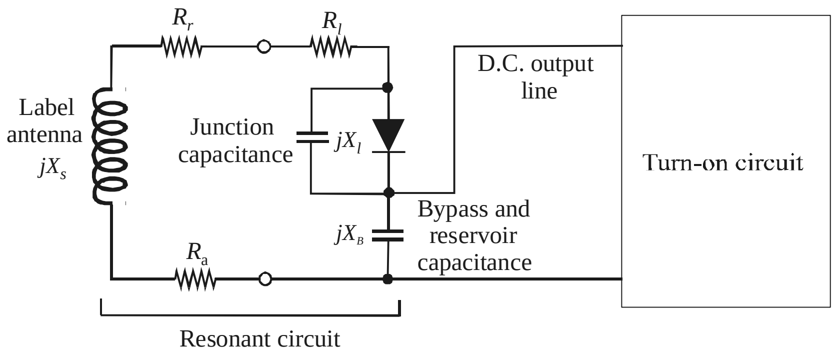

Figure 2: label rectification circuit

The antenna ohmic losses can be ignored since the antenna construction in a good design can be a slot antenna containing a significant amount of copper. In addition the series combination of the impedance jX_l and jX_B will be approximately equivalent to that provided by the diode junction capacitance, as the reservoir capacitor has a relatively larger capacitance of the order of 100 pF. It is assumed that no d.c. power is removed from the diode. By shaping the antenna and its connection points appropriately, we will see that an impedance match between R_r and R_l can be achieved.

Determining the minimum power required to produce one volt across the reservoir capacitor of the label circuit requires care. The procedure involves: selecting a suitable diode; setting up an impedance matching circuit; setting up an RF rejection circuit and minimising damping caused by radiation.

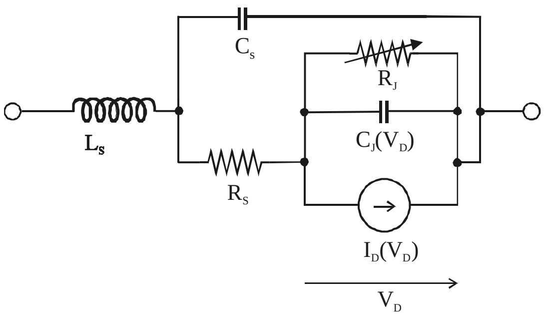

Figure 3: High frequency diode model

A model of a Schottky diode at high frequencies is presented in Figure 3 R_s is the parasitic series resistance of the diode, L_s is the series package inductance and C_s is the package capacitance, where the capacitance C_j which depend on the bias voltage V_d is the voltage across the junction. Current CMOS manufacturing techniques can produce small Schottky diodes with junction capacitances (diode depletion layer capacitance) ranging from 0.1 pF to 1 pF. However a Schottky junction is relatively delicate and sensitive to excessive RF power. RFID applications may work in poorly controlled environments where high power may cause the diode to burn out. Hence in an application it is important to use power limiters to protect the sensitive Schottky diode.

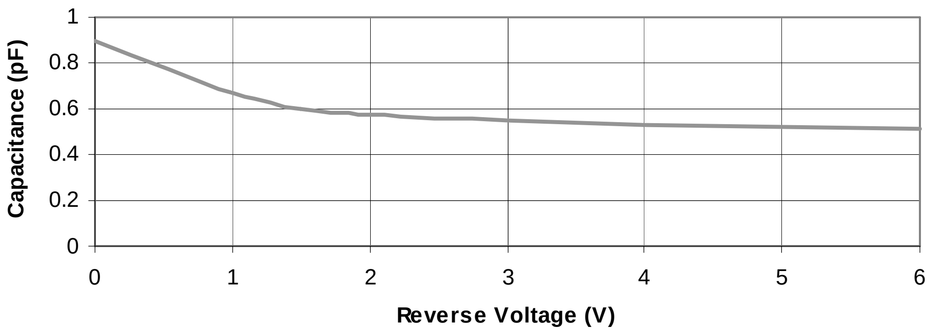

Figure 4: Junction capacitance: Variation of the diode junction capacitance as a result of the reverse voltage

Experiments detailed in the paper utilised the Hewlett Packard 5082-2835 Schottky diodes [4] (a surface mounting version of the same diodes are available as HSMS-2820) to evaluate the feasibility of a resonant rectifier. These are good candidates for the application due to the range of its capacitance (1pF – 0.5 pF) and low cost. Figure 4 provides a plot of the variation of the junction capacitance as a result of the reverse biasing voltage across the depletion region.

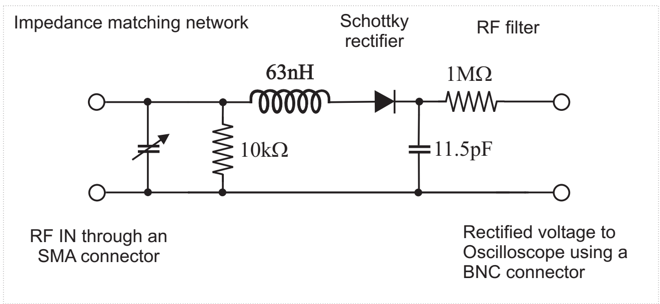

Figure 5: Simple diode rectification circuit

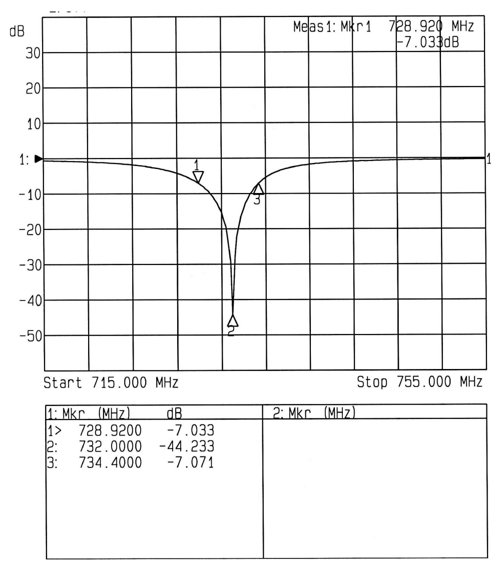

Figure 6: Low power Q: the return loss plot obtained with the network analyser output power level set to -35dBm indicates a low power Q of approximately 130.

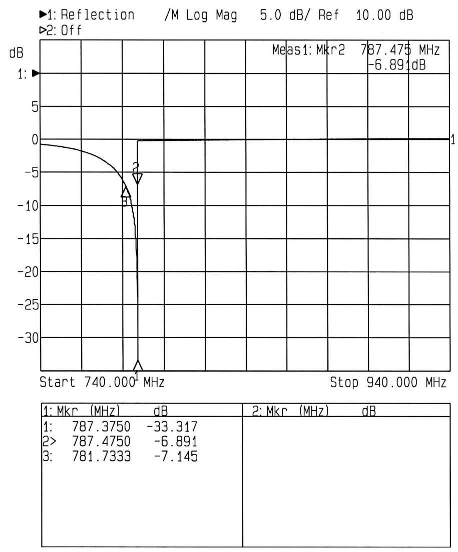

Figure 7: High power Q: the return loss plot obtained with the network analyser output power level set to -19dBm depicting the non-linearity of the circuit response.

As the measurement method uses a network analyser to deliver RF power and to measure the return loss, the RF input port of the measurement circuit requires an impedance matching network with a capacity for external adjustment. This is provided by an adjustable trimmer capacitor in series with stray inductance of the capacitor connections. The 63 nH inductor serves to form a resonant circuit with the junction capacitance of the diode (in a practical RFID label this inductance will be provided by the antenna of the label). Measuring the output voltage from the reservoir capacitor requires filtering to remove all the RF content in order to minimise radiation from the output connection before the voltage is measured across the reservoir capacitor. A schematic of the diode rectification voltage measurement circuit is provided in Figure 5.

Using a return loss plot, the quality factor of the resonance of the impedance matching circuit was found to be around 35; hence it is relatively broadband in relation to the quality factors expected in the diode resonance. The Q is also important in determining the losses of the circuit as we require most of the RF energy to be localised in the diode resonance.

The return loss plots provided in Figure 6 with the diode connected can be utilised to obtain the low power Q of the diode resonance while the plot in Figure 7 provides a return loss curve under high power and thus can be used to obtain the high power behaviour of the diode as the source frequency is swept.

The non-linearity of the circuit response shown in Figure 7 at high power precludes a meaningful definition of high power Q.

2.2.1 Power requirements for a zero power turn-on circuit

While sweeping across a 2 MHz frequency range the minimum UHF frequency input power required to obtain a d.c. output of 1 volt from the circuit was -16.20dBm. The resulting return loss curve showed that over 90% of the incident power at 915 MHz is feeding into the diode resonance.

Calculation, using standard far field antenna formulae, of the range at which, for favourably oriented antennas, a reader with antenna gain of 6 dB and output power of 1W, (as is allowed under the US regulations [5]) will provide this available source power from a tag antenna of gain 1.5 gives a range of 12.6 m.

However an interesting and important phenomenon can be observed when the signal sweep bandwidth at high power is reduced. Unless the sweep begins at a frequency that is somewhere near the low power resonance frequency, and follows upward in frequency as the diode develops voltage and begins to raise its resonant frequency, the full diode output will not be obtained. Zero power turn-on circuits have a limited range of operation due to the large voltage needed. However zero power turn-on circuits are useful for extending the battery life of battery assisted backscatter labels.

2.2.2 Power requirements for a low-power turn on circuit

An alternative means that can still exploit the diode resonance in a turn on circuit is to compare a small d.c. voltage developed across a diode with an internal reference voltage, and to activate a switch when the rectified voltage exceeds the internal value. In order for the low power turn on circuit to be useful the current drain in its “off” state must be low with respect to the self discharge current of the battery. Unlike the previous turn on circuit the present design is triggered by a small d.c. voltage, rectified and amplified by diode resonance where the minimum value will be dictated by rectified RF noise [6].

Experimental evidence has proved that a minimum RF power of -46dBm is required at resonance to obtain a 5mV d.c. output from the reservoir capacitor. Calculation, using standard far field antenna formulae, of the range at which, for favourably oriented antennas, a reader with antenna gain of 6 dB and output power of 1W, will provide this available source power from a tag antenna of gain 1.5 gives a range of 390 m. The operation range makes these turn-on circuits suitable for independent reply generating active labels.

3. DESIGN AND IMPLEMENTATION

A circuit design that utilizes the diode resonance to turn a battery powered RFID label “on” can be designed in a number of ways. The primary concern is the design and implementation of a Schottky diode with characteristics that are similar to those studied in HSMS-2820. In order for the circuit design to be cost effective it requires the diode design to be fabricated using a standard CMOS process. There is a range of possible designs for achieving such a goal [7]. The layout of the CMOS diode used in the turn-on circuits is outlined in Figure 8 while Figure 9 gives a voltage and current plot of the diode.

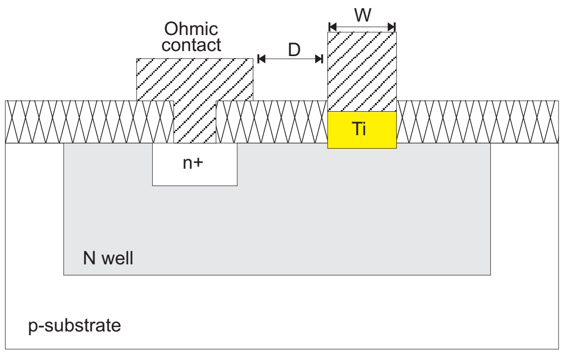

Figure 8: Cross-sectional view of the Schottky barrier diode. Here the Schottky diode contact width is *W*, and the separation between the Schottky contact and the Ohmic contact is *D*.

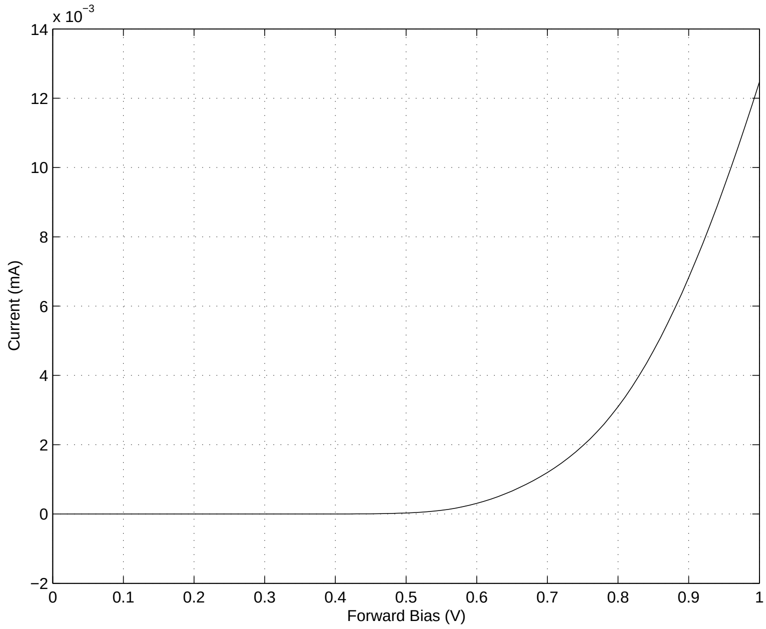

Figure 9: Measure IV curve of the CMOS Schottky barrier diode

3.1 Low power turn-on circuit

Figure 10 shows a fully integrated turn-on circuit which requires a small dc voltage to be developed by a Schottky diode rectifier, which is compared with an internal reference voltage, and activates a switch when the rectified voltage exceeds the internal value. The sensitivity is adjusted by changing the internal reference voltage. The inductors are required to match the input to a 50 Ω test input, but in practice these elements would be incorporated into the antenna [6].

For maximum sensitivity, the circuit shown in Figure 10 requires testing and trimming of the sensitivity for each individual die on a wafer. The circuit was trimmed to achieve approximately 4 mV sensitivity, that level thought to be more sensitive than necessary. The circuit sensitivity changed from 5.8 mV at –3 ^{o}C to 4.7 mV at 80 ^{o}C. The current consumption was 56 nA at 26 ^{o}C.

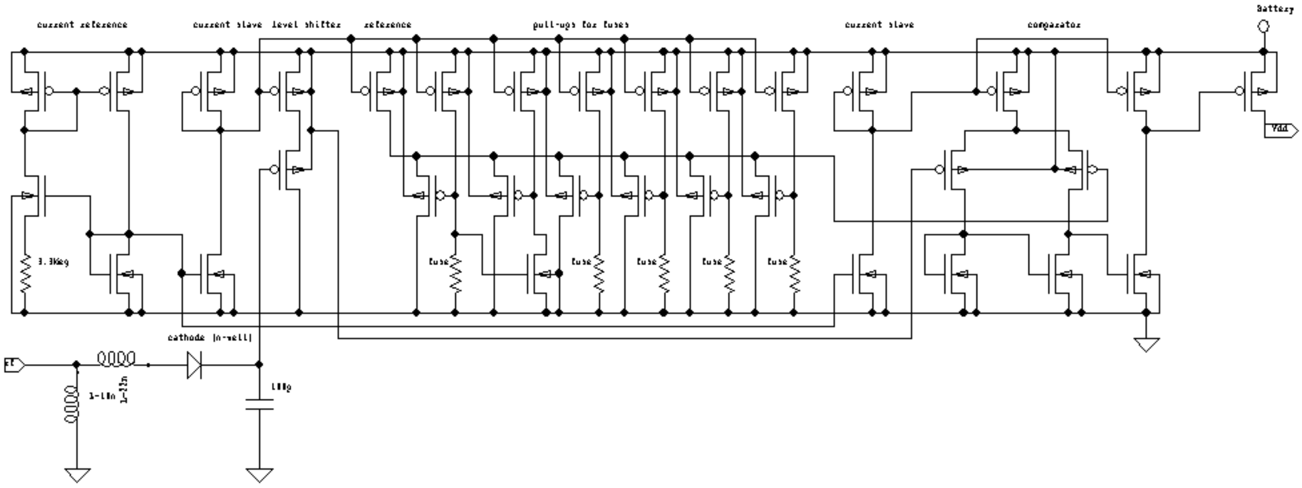

Figure 10: A turn-on circuit based on rectified input voltage of 5 mV d.c. output based on a internal reference voltage with trimmable sensitivity.

The circuit was constructed using a standard 0.5 μm digital process. The Schottky diode was made by placing metal over a minimum size (0.5 μm x 0.5 μm) contact cut to a region of minimum size (3.5 μm x 2.4 μm) n-well. The capacitance from the n-well to p-substrate was 4.6 fF. The diode had a dc voltage drop of 0.56 V at 427 μA, and an RF sensitivity of 14.23 mV/μW at 915 MHz when developing a rectified dc voltage of 4 mV. As a comparison, an HP HSMS-2820 Schottky diode had an RF sensitivity of 40 mV/μW, under similar conditions. At 915 MHz the diode had a series impedance of $21.10 + j173.66\ \Omega$ when the rectified d.c. output was 4 mV.

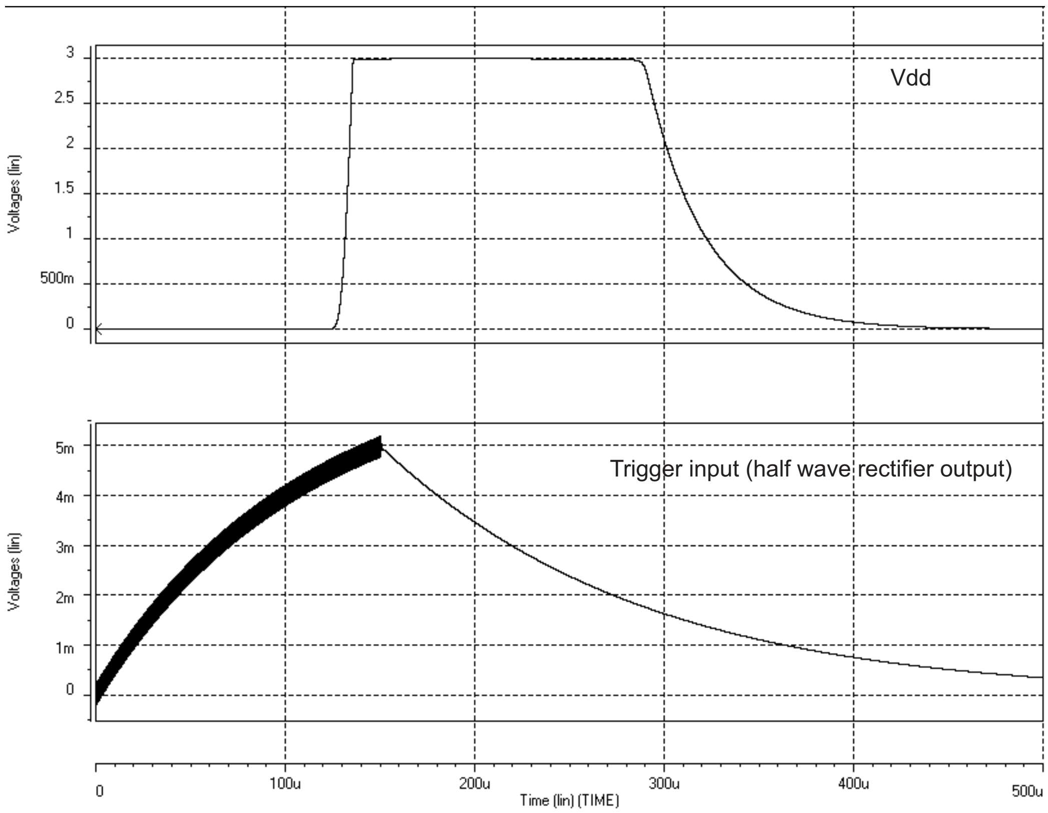

Figure 11: Simulated results for the low power turn on circuit implementation in Figure 9 using a HSPICE diode model for the fabricated CMOS Schottky diode.

A rectified voltage of 4.2 mV was achieved for a received power of –35.3 dBm. Calculation, using standard far field antenna formulae, of the range at which, for favourably oriented antennas operating at a frequency of 915 MHz, with antenna gain of 6 dB and output power of 1W (as is allowed under FCC regulations for the UHF ISM band [5]), will provide this available source power from a label antenna of gain 1.5 gives a range of 117.4m. The practical range is less than that expected from the experimental data for the HSMS-2820 diode. This is due to the performance of the diode. However achieving better performance using standard CMOS technology is a difficult task. However the circuit still triggers at over 100 m for the trimming settings above.

If maximum sensitivity is not required the trimming transistors are formed from discrete blocks of fixed geometry transistors, rather than from transistors of varying lengths or widths. Typically foundries provide SPICE data for a few fixed geometry devices, so by using multiples of these devices the simulations provide more accurate results than when custom geometries are used. The trimming cuts may then be based on the average of the test results of four or five circuits distributed across the wafer, i.e. all die on a wafer are trimmed in the same manner. Monte Carlo simulations provide a good indication of the expected spread of sensitivities across the wafer.

Simulations were performed with: wafer based parameter variations V_t (AVTO), γ (AGAMMA), and K_p (AKP); and lot based parameters T_{ox}, V_{tex}, β, γ, L_{eff}, and W_{eff} to evaluate the performance of the circuit piror to fabrication and testing. Simulation results indicate (refer to Figure 10) that the turn on circuit performs adequately at a minimum power of 700 nW. This result correlates with the measurement results performed previously with HP Schottky diodes. Figure 11 shows the simulated output for a 915 MHz, -61.55 dBW pulse input to indicate the circuit switching on and, later, off after the removal of the excitation.

Calculation, using standard far field antenna formulae, of the range at which, for favourably oriented antennas operating at a frequency of 915 MHz, with antenna gain of 6 dB and output power of 1W, will provide this available source power from a label antenna of gain 1.5 gives a range of approximately 70m (under FCC regulation for the UHF ISM band [5]).

3.1.1 Circuit performance

A low power turn on circuit totally integrated on a digital CMOS process including the Schottky diode has produced a high sensitive result. However the circuit does have a low sensitivity to temperature variation as a -3 ^{o}C to 80 ^{o}C variation results in 1.1mV change of sensitivity. However this can be compensated by trimming at the wafer stage. The circuit also operates reliably at a stand-by current of 56 nA. Figure 12 shows the response of the circuit to a 5 mV input pulse of duration 4ms. This is at the threshold of operation and Figure 13 shows the response of the circuit to a 6 mV input. The response time of the circuit can be observed to be 1.5 ms.

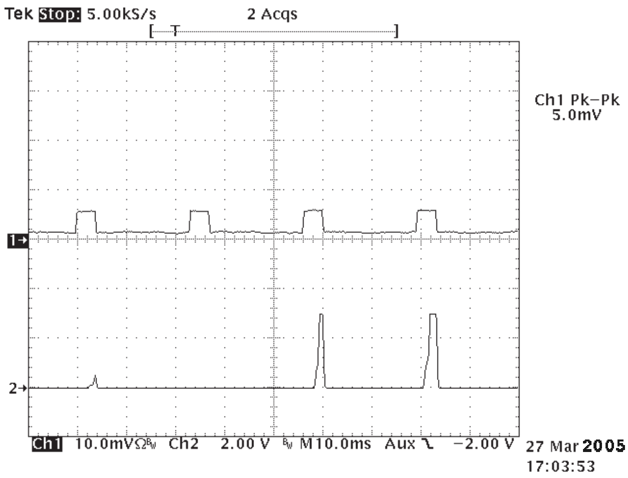

Figure 12: Response of the circuit to a 5mV rectified d.c voltage

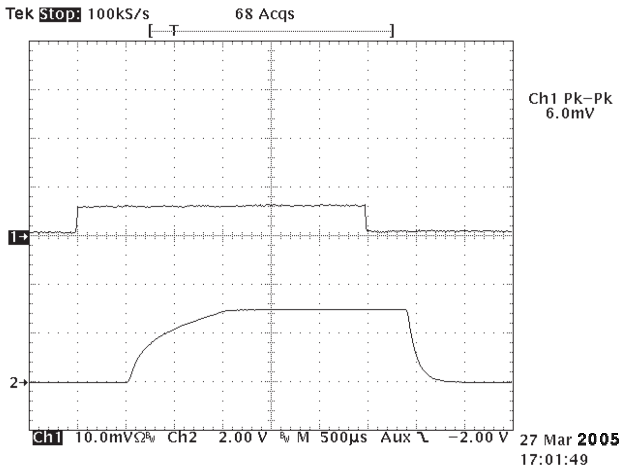

Figure 13: Response of the circuit to a 6mV rectified d.c voltage.

3.2 Zero power turn on circuit

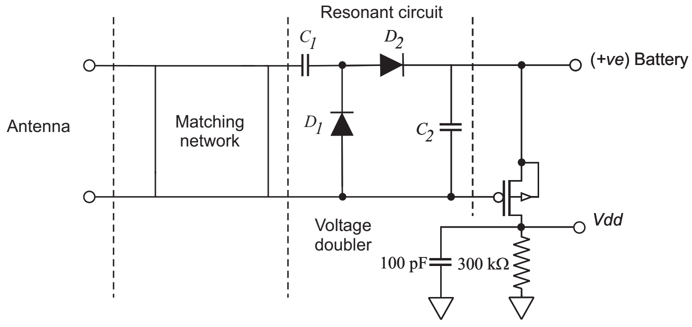

Figure 14: Turn on circuit implementation.

The proposed novel turn-on circuit below is adequate and cost effective for a backscattering active label. In this proposal a p-channel FET was used as a switch to control the power supply to a labels control circuits and can be triggered by the incident RF radiation on the antenna. Thus the power generated and amplified by the diode resonance can be utilized to turn a p-channel FET from an off state to an on state. Figure 14 gives the implementation of the turn-on circuit while Figure 15 gives an implementation used in an HSPICE simulation of the circuit. In the circuit used for simulations (Figure 15), the antenna was modelled as a voltage source with an impedance of 50 Ω. Again, the inductors are required to match the input impedance of the rectifier structure to the 50 Ω test input.

Simulation results indicate (refer to Figure 16) that the turn on circuit performs adequately at a minimum power of -43 dBW at the resonant frequency of the turn on circuit (915 MHz). This result correlates with the measurement results performed previously with HP Schottky diodes. However the simulated results indicate a lower power requirement to generate the required turn on voltage this is due to the better performance of the HP diode in relation to the Schottky diodes fabricated using standard CMOS technology. Figure 16 shows the simulated output for a 915 MHz, -43 dBW pulse input to indicate the circuit switching off after removal of the excitation. The simple circuit requires the excitation for the time of transmission, but could be triggered by an RF pulse by latching the battery switch on for the time of transmission.

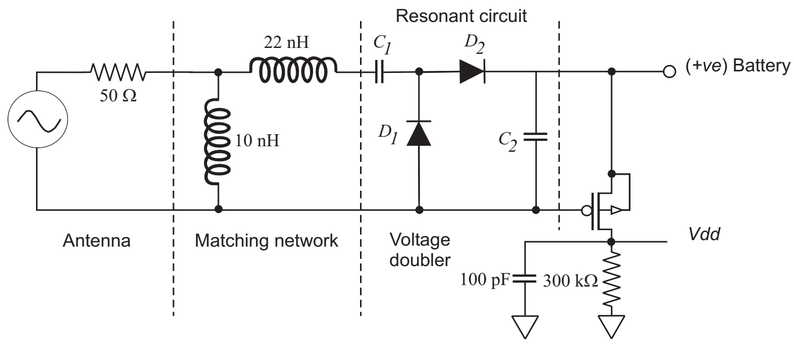

Figure 15: Turn on circuit implementation used in an HSPICE simulation.

Calculation, using standard far field antenna formulae, of the range at which, for favourably oriented antennas operating at a frequency of 915 MHz, with antenna gain of 6 dB and output power of 1W (as is allowed under FCC regulation for the UHF ISM band [5]), will provide this available source power from a label antenna of gain 1.5 gives a range of approximately 10m. Operation at this power level would thus enable a backscattering tag to be turned on and off in the range of 10m under ETSI or FCC jurisdiction.

The zero power turn on is a practicable design that can be fabricated using a standard CMOS process. Simulation results and test performed using discrete components show that the diode fabricated is adequate to obtain a desired level of performance for a zero power turn on circuit. However the complete fabrication of a zero power turn on circuit was not available for testing at this stage and is currently under fabrication.

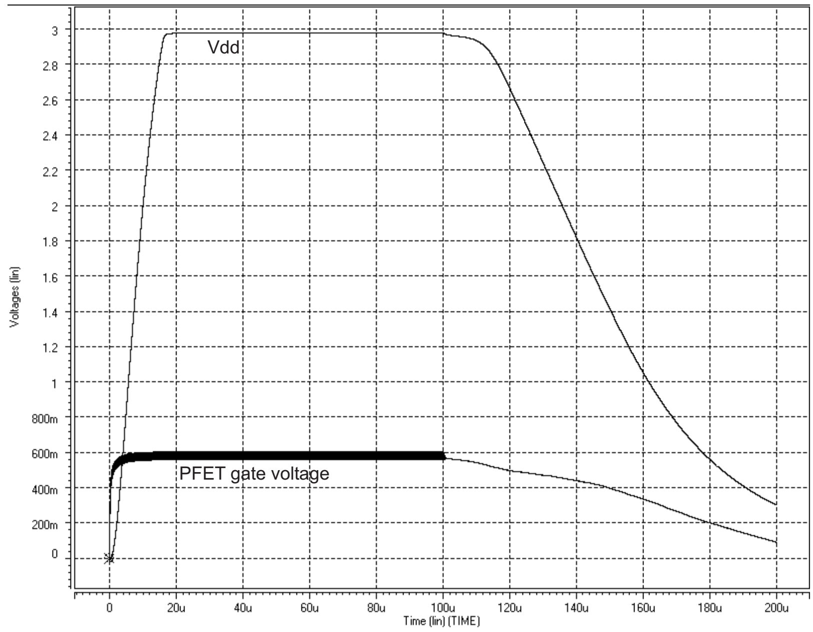

Figure 16: Simulated results for the turn on circuit implementation using HSPICE diode model for the fabricated CMOS Schottky diode.

4. CONCLUSIONS

The development of active labels and sensors will eventually involve the incorporation of turn-on circuits. We have presented some concepts and a number of ways in which they can be exploited; however not all the alternatives my be practicable. The concept provided for a zero power turn on circuit in Section 4 involves the design of a turn-on circuit that functions by sweeping the excitation across a UHF bandwidth. This concept is a practicable alternative and it is illustrated through performance measurements taken in a scenario modelling a far field, and through range predictions under favourable conditions based on that scenario.

The concepts outlined and tested were used to design, analyse and simulate a zero power turn-on circuit, while the results of the measurement studies were used to design analyse, simulate and fabricate a low power turn on circuit.

The circuits presented in the paper can be fabricated on a single poly, single metal CMOS process, allowing easy incorporation into existing transponder designs. The low power turn-on circuit has trimmable sensitivity to allow for process variations or different sensitivities. The circuit's sensitivity exhibits minimal change with temperature, allowing the trimming to be set at room temperature at the wafer testing stage. The low power turn-on circuit is triggered by a small d.c voltage, rectified from an RF signal, the selected minimum value being dictated by rectified RF noise, and the intended operational temperature range. At UHF the rectifier needs a CMOS process supporting Schottky diodes or an external device. Test results show that the practical realisation of the above concept in active labels is a possibility.

A turn on circuit is permanently powered, however for it to be effective; the current drain of the turn on circuit must be low with respect to the self discharge current of the battery. The low power turn-on circuit presented in the paper presents a current drain of less than 5% of the self discharge currents of a typical 3.5V 750mAh lithium battery while the zero power turn-on circuit presents a current drain of less than 0.1%.

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