CONCLUSION

A wide range of solutions for implantable integrated circuit design has been presented in the preceding chapters, solving many of the common difficulties encountered in such designs. The restrictions posed by the implantable nature of the circuits and systems are related to the scarcity of external resources, leading to a need for the integration of all the functionality on a single chip. The resources which are unavailable to the implanted chip are in essence all support functions which are normally taken for granted in chip design, being the supply voltage, biasing signals, voltage references, the time reference. The available power is also severely limited, but that is a limitation which is common to most types of portable electronic devices. In addition to the resource limitations, an implantable IC must also cope with the special mode of operation which mixes data and power transfer in a single signal.

The importance of the inductive link for the system design is emphasized in the first chapter, which presents a short overview of the standard circuit-level description. The standard description is however limited in some ways, since it almost completely ignores the connection between the physical geometry and the circuit representation. It can therefore not be used to predict the range of a link, nor to predict the dependence of the power transfer on the distance. The difficulty lies in the complex dependence of mutual and self-inductances on geometrical details. We have however developed an expression, based on geometrical approximations, which can predict quite accurately the distance dependence of operational parameters, and these expressions have been verified experimentally.

The special method used for inbound data transmission, which is basically modulation of the power transmission, places some unusual demands on the receiver circuits. The additional requirement of having a self-contained receiver, which does not rely on digital signal processing, limits the range of available receiver types. We have developed a completely self-contained receiver for amplitude shift keying (ASK) modulation which is compatible with these requirements, while using a very low supply current. The receiver can handle variable modulation depths, and spans the modulation range of the most efficient transmitter architectures. Where previous designs have relied on pre-set modulation levels or constant modulation of the carrier to set the detector levels, our design does away with such limitations. The receiver operates over a wide range of carrier frequencies and bit rates, corresponding to the prevalent values used in inductively coupled systems, and can without difficulty be modified to extend this range.

The power supply management methods are treated separately, as many of the special conditions for implanted ICs have a large impact on the power supply quality. We have developed and implemented a two-terminal overvoltage protection circuit, or a shunt regulator in other words, which is completely self-sufficient. This circuit can be used instead of the commonly used passive protection circuits, internal or external, and is compatible with plain CMOS processing. The knee voltage of the protection circuit is accurate to within a few percent, due to the use of an integrated bandgap voltage reference. The protection circuit spans a very wide current range, and can protect the IC against the worst power transients without drawing a noticeable current when it is not needed. The stability criteria of the shunt regulator were derived, along with an expression for the maximum shunt current range. An implementation of the protection circuit confirmed their validity, and performed according to expectations, showing that this solution is superior to those used in previous designs.

The rectification of the carrier for the conversion to a DC supply voltage was addressed, with the objective being complete integration in a CMOS technology. A bridge rectifier implementation was developed which avoids the pitfalls of loss currents stemming from the CMOS parasitic elements. The loss currents were reduced by a large factor by using p-channel MOS transistors in the rectifier bridge and biasing them in weak inversion. The speed penalty normally associated with weak inversion operation is not relevant in this case, since the modest increase in capacitance can be absorbed in the antenna tuning capacitor. The ratio of the desired rectifier current to the parasitic loss current was derived, and it was shown that a very large current ratio could be attained, effectively reducing the losses to zero. The dependence of the improvement on layout factors was also examined, and an alternative improved layout was suggested.

Any integrated system chip of the type described here will unavoidably consist of a mix of analog and digital circuits. Due to the single shared supply point of the entire system, the digital supply current transients are seen unfiltered by the analog part. We have proposed the use of an on-chip linear regulator, both to provide isolation between the digital and analog circuits and to reduce the supply current of CMOS logic. We have described a regulator design which is based on a previous design, but improves on it by extending its supply voltage range.

On-chip generation of bias signals is almost invariably implemented by using degenerate current mirrors, due to the predictability of the resulting bias currents and the low sensitivity to supply voltage variations. If these bias generators are implemented in CMOS, the degenerate current mirrors must be biased in weak inversion. We have analyzed the impact of moderate inversion effects on the resulting bias current, and present guidelines for the required biasing level to obtain a given maximum deviation from the ideal case.

The reset signal is another example of a general circuit resource which must be generated internally in an implanted system. Different reset strategies for mixed analog/digital systems were discussed, and a new reset signal generator was presented. The reset circuit is based on supply voltage sensing using a comparison of two different functions of the supply voltage. The circuit provides a sufficient amount of hysteresis in the reset signal threshold to avoid false triggering due to supply voltage fluctuations, and uses very little current.

An overview of system design for implantable ICs was provided by the use of two examples. The first example is an implantable neural stimulator chip, whose initial design predates the time frame of this project. The chip was however finished during the course of this study, and it is used to illustrate some of the interface and packaging problems common to implantable systems. The chip was flipped onto an alumina substrate with discrete support components, along with a novel thick-film antenna coil implementation. Despite the unwanted interaction of the electromagnetic field with some of the externally routed signals, the system assembly did prove to be functional. This chip did not incorporate any of the integration solutions presented in this thesis, but had it done so, the discrete component count would have been far lower and the system would have been more resistant to external disturbances.

The second system chip example is a transceiver which does use the methods presented here to reduce the external component count to the bare minimum. The transceiver IC is conceived as an interface between implanted sensors or actuators and the external (non-implanted) apparatus. The transceiver is placed in close proximity to the surface of the body, where the field from the transmitter is strongest. The high field strength and coupling coefficient permit effective inbound data and power transmission, and allow the use of passive load modulation for outbound transmission. The sensors or actuators are connected to the transceiver chip by a two-wire bus for serial transmission. This bus is implemented physically by a length of Cooper cable, which also carries the supply power to the sensors or actuators. The main point is to perform any signal processing and conversion between the digital and analog domains locally, at the electrode interface, to eliminate the effect of induced signals and noise coupling.

In summary, the main subject of this book is the development of CMOS circuit solutions for implant functions which have previously only been possible with advanced processing techniques, or by the use of external components. We present methods to drastically reduce the component count and interconnect complexity of implanted ICs, and present an example of a system IC which incorporates these methods.

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