Directions for RF controlled intelligent microvalve

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ABSTRACT

In this paper, we consider the novel concept of a Radio Frequency (RF) controllable microvalve for different medical applications. Wireless communication via a Surface Acoustic Wave Identification-mark (SAW ID-tag) is used to control, drive and locate the microvalve inside the human body. The energy required for these functions is provided by RF pulses, which are transmitted to the valve and back by a reader/transmitter system outside of the body. These RF bursts are converted into Surface Acoustic Waves (SAWs), which propagate along the piezoelectric actuator material of the microvalve. These waves cause deflections, which are employed to open and close the microvalve. We identified five important areas of application of the microvalve in biomedicine: 1) fertility control; 2) artificial venous valves; 3) flow cytometry; 4) drug delivery and 5) DNA mapping.

Keywords: Microvalve, SAW, ID-tag, fertility control

1. INTRODUCTION

Micromachining processes are applied to the construction of a wide variety of microstructures in different areas of society. Many types of microstructures are produced for different tasks. Microflow devices are microstructures which are able to control or sense flow in the order of μl/min.[1] The most common microflow devices are the microvalve and the micropump. These aim to regulate the movements of fluids and gases in the order of μl/min. Microvalves have a very small dead volume and are able to realize precise control for a small flow as well as possessing a fast response time. Microvalves are classified into two categories: active microvalves (with an actuator) and passive microvalves (without an actuator). The performance of an active microvalve depends strongly on the features of its actuator. Thus, the physical parameters like the size, force and displacement of the microvalve are determined by the performance of the driving actuator principle. These parameters are significant for different applications of the microflow device.

There are three main actuator principles for an active microvalve: electromagnetic, electrostatic and piezoelectric. The electromagnetic actuator principle may be applied to pneumatic controls.[2] It consists of a combination of a coil and a ferromagnetic material. A magnetic force is generated in the ferromagnetic material when it is placed in the magnetic field of the coil system. The electrostatic actuator principle commonly consists of two electrodes. A resultant force is generated by the application of a DC potential between these two electrodes. This principle could be used in drug delivery pumps.[3] The piezoelectric actuator principle is achieved by applying a voltage alternation to an piezoelectric crystal and is used in gas control systems.[4] This alternating voltage causes a deformation of the piezoeletrical material used for the actuation of the valve. Microvalves have different structures resulting from their activation forms. Only a certain actuator may be matched to a desired application.

For special applications like implantation in the human body, the microvalve should contain certain vital features. The material of the microvalve has to be compatible with the surrounding tissues and organs to prevent a dangerous or deadly interaction between the valve and the human body. Furthermore the reliability can be increased if the function of the microvalve is monitored and controlled from outside via wireless communication.

The employment of wireless communication in combination with the microvalve serves to fulfill some essential requirements. The microvalve needs energy to drive its actuator. It receives this energy via the wireless communication. The energy serves to perform the control function of the valve. This includes regulating the movements of fluids

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by opening or closing the orifice of the microvalve. Furthermore, it is required that the communication link is stable and unaffected by the presence of bodily fluids and surrounding tissues. These requirements are met by the use of RF pulses, which are transmitted by a reader/transmitter unit (outside the human body) to a coded transponder (inside the human body) and *vice versa*. This coded transponder or so called Identification Device (ID-tag) is printed on the surface of the piezoelectric actuator of the the microvalve. The RF pulses are received and converted by the ID-tag to Surface Acoustic Waves (SAWs). These SAWs propagate along the surface of the piezoelectric actuator material. At the same time, they cause a deformation of the actuator material, which is used to open or close the microvalve. The SAWs are reflected by electrodes which have an arrangement similar to a bar code. They are reconverted to RF response signals and retransmitted by the ID-tag to the reader/transmitter unit. There, the receiving RF pulses are evaluated by signal procedures.

This remote ID-tag is completely passive and needs no extra power supply. It is employed to locate the microvalve in the human body. In this paper, we consider wireless RF controlled microvalves which use the principle of ID-tags. Furthermore, we consider applications in special fields like the fertility control, artificial venous valves, flow cytometry, drug delivery and DNA mapping.

2. RAYLEIGH SAW DEVICES

Surface acoustic wave devices find a variety of applications in various microstructures (pressure, strain and temperature sensors). Rayleigh surface acoustic waves can be generated at the free surface of an elastic solid. The generation of such waves can be achieved by the application of an alternating voltage to a metal, parallel, planar structure which is deposited on the free surface of a piezoelectric solid (Quartz or Lithium niobate). This type of structure is called an Interdigital Transducer (IDT). The basic concept of a two port SAW device consists of two IDTs which are deposited on a piezoelectric substrate. One of them acts as an input and the other as an output device as shown in Figure 1.

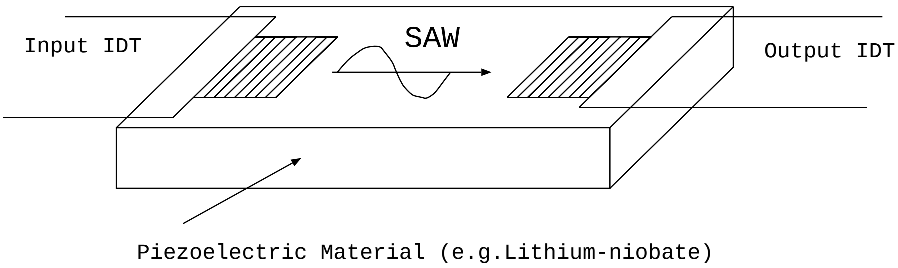

Figure 1. Rayleigh Surface Wave Device.

The input IDT is employed to convert the applied voltage variations into mechanical surface acoustic waves. The other IDT is used to receive these mechanical SAW vibrations and to reconvert them back to an alternating voltage. These devices are reciprocal in nature, and as a result signal voltages can be applied to either IDT with the same end result. The area between the two IDTs is used to sense the environment. Surface acoustic waves have special properties which are important for their sensing tasks. Thus, the energy of Rayleigh waves is concentrated within one wavelength of the substrate. The principle of SAW devices is based on the fact that any changes in the mechanical and electrical boundary conditions of the Rayleigh wave will cause a change in the characteristics of the propagating wave. This makes the surface of the substrate between the two IDTs particularly sensitive to any changes in the environment. That fact is used in the principle of SAW sensors where the traveling time of the surface acoustic waves between the IDT and the reflectors will change with the variations of any physical variables (pressure, strain and temperature).[5–11]

2.1. SAW ID-tags

As an alternative to the use of a two port SAW device, the receiving port can replaced by a series of reflectors, which are also metallized finger electrodes. The output IDT can be directly connected to a microstrip antenna to receive and to transmit RF signals. This fact suggests that it is possible to realize passive, wirelessor remotely operable

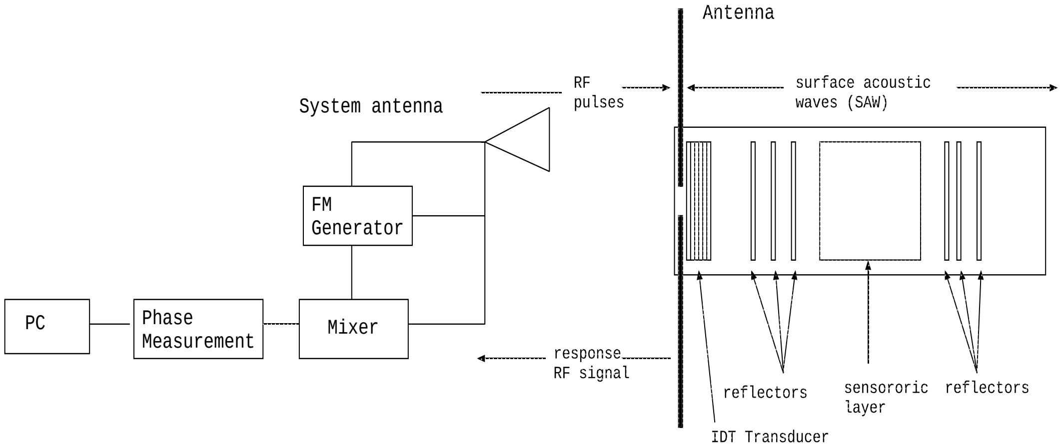

Figure 2. Principle of a passive wireless SAW ID-tag with no power at its location and a reader/transmitter station with system antenna.

SAW devices or SAW Identification-marks (SAW ID- tag). The basic principle of a passive wireless SAW ID-tag is shown in Figure 2.

The IDT antenna module is able to convert the microwave signal from the air to a SAW signal on the wafer surface and *vice versa.* The reading system has a linear Frequency Modulated (FM) signal generator. The FM signals are transmitted by the system antenna. The signals are received by the device antenna and converted by the IDT to SAWs propagating along the surface of the wafer.[8]

The echoes from the reflectors are reconverted and retransmitted by the device antenna as electromagnetic response signals of the system. The response signals form a sequence of short pulses in accordance with the number and position of the reflectors on the crystal surface. The signal response of a SAW ID-tag (Figure 3) is a pattern, like a bar code. The time delay of every partial response pulse depends on the SAW propagation velocity, which is affected by several physical quantities (temperature, pressure and strain) and the distance between the IDT and the reflectors.[12]

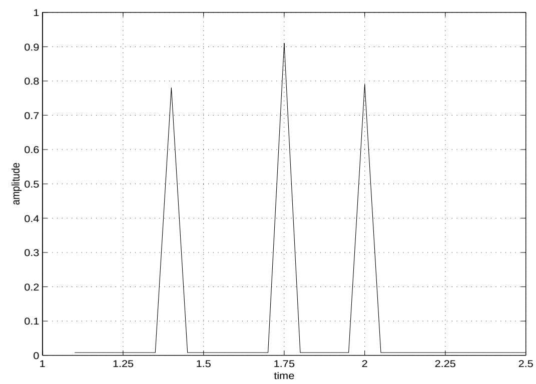

Figure 3. Principle of a Response Signal for an SAW ID-tag.

Thus, the echo signals are delayed copies of the transmitted FM signal. A mixer which takes the transmitted FM as a reference signal, outputs the signals of the frequency difference between the echoes and the transmitted signals. Because the transmitted signal is linear frequency modulated, the frequency difference is proportional to the delay time.[7–11]

The pattern of the different echoes of the surface acoustic wave and the corresponding response radio signal is used for remote readout of SAW Identification-marks. To provide individually coded ID-tags a code is defined by a number of reflector positions, each representing one "bit" of a digital number. The value depends on whether a reflector is placed on the specific position or not. For instance, an existing reflector encodes a logical "1", a missing reflector is the equivalent to a logical "0". The signal attenuation depends on the number of reflectors deposited on the surface. The reasonable code length is limited by the signal attenuation. Typical maximum code lengths are in the order of 32 bits.[12] Furthermore, the location of the ID-tag can be indirectly determined by the measurement of the propagation time of the RF signal from the reader/transmitter unit to the ID-tag and back.

3. MICROVALVE STRUCTURE AND PRINCIPLE

The principle structure of the microvalve is shown in Figure 4. The valve belongs to the group of 3D MEMS and is fabricated by Micro Stereo Lithography (μSL). The μSL is used to create 3D MEMS devices with high aspect ratio and complex geometry. Basically, μSL deals with the generation of 3D structures from UV radiation curing polymers. The curing is done point by point or layer by layer using either He-Cd laser or a Xenon lamp.

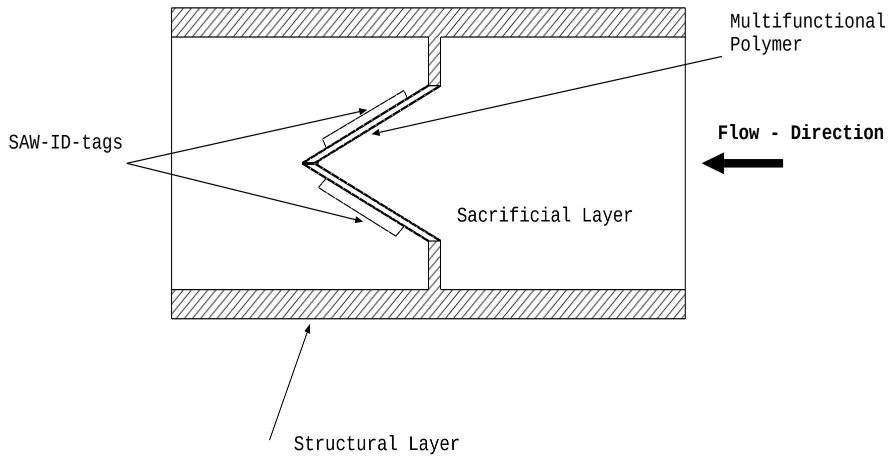

Figure 4. Cross sectional view of the microvalve with structural and sacrificial layer.

This microvalve uses two different kinds of polymer layers: one is the structural layer and the other is a sacrificial layer. The structural polymer layer is used for the production of the whole device frame of the valve, whereas the sacrificial polymer layer is employed to create a cavity for the fluid flow. The closure element of the valve is partly made out of a cantilever multifunctional piezoelectric actuator polymer. An ID-tag is printed on this actuator crystal.

The principle of SAW propagation on the multifunctional polymer is used for the actuation of the microvalve. This actuator polymer crystal was developed at Penn State University. The polymer is suitable for biological applications, because it is compatible with the human body.[5] Moreover, this polymer has special conductive and possibly piezoelectric or ferroelectric properties, which can be employed for micro-actuators in 3D MEMS structures.

The driving energy for the piezoelectric polymer actuator is provided by RF pulses. The schematic in Figure 2 shows the basic operating principle of the microvalve. The ID-tag on the valve is "connected" to the reader/transmission station via a wireless communication link. In the initial state, when no RF signal is applied to the ID-tag, the microvalve is closed. If RF pulses are transmitted from the reader/transmission unit to the ID-tag, the received and converted RF pulses propagate as SAWs along the surface of the cantilever polymer and cause deformation of this material. These deformations are employed to open the microvalve and alter the distance between adjacent reflectors. This results in an additional delay time of the reflected signal which can be use to detect the strain of the polymer material.[8] Thus, at the same time the diameter of the orifice of the microvalve can be read out when the partial reflected and delayed signals of the ID-tag are evaluated by the reader/transmission unit. Furthermore, the propagation time of the RF pulses from the reader/transmitter system to the ID-tag and back can be used to determine the location of the valve. This is essential for the employment of the microvalve in the human body.

4. APPLICATIONS

The previously described principle of a RF controlled microvalve finds a variety of applications especially in the medical sector. Because of its characteristics and features, the valve is ideal for use as an implant in the human body. In the following section we discuss the application of the microvalve to 1) fertility control, 2) artificial venous valves, 3) flow cytometry, 4) drug delivery and 5) DNA mapping.

4.1. Fertility Control

A variety of methods of conception control are widespread. The choice of a suitable method is quite difficult, because each has specific strengths and weaknesses, the potential risks and benefits must be carefully analyzed on an individual basis.[13] The goal in the research of fertility control is to find new procedures which prevent the chemical strain on organs of the female which is caused for instance by the "pill" or to decrease the probability of prostate carcinoma of the male which is caused by surgical vasectomy.[14] In the latter case, it is desirable to reduce surgical procedure as well. Since the restoration of fertility after a reverse vasectomy does not always result in a restoration of fertility, strong efforts are made to develop a novel reversible vasectomy method without surgical strain on the human body.

When the passive, wireless and remotely RF controlled microvalve technology presented above is utilized, it reduces the surgical strain on the body of the male and female, and makes it possible to restore fertility with relative ease.

The RF controlled microvalve is inserted into the *vas deferens* of the male or into the *ovarian duct* of the female. Since the inside diameter of the *ductus deferens* (0.3 mm) of the male and the *ovarian duct* (3 mm) of the female differ in the order of 10 times, different sizes of microvalves are used for the purpose of fertility control. In addition the size of the sperm (5 μm long and 3.5 μm wide) and of the ovum (0.25 mm) differ in the order of a factor of 5000. Thus, two different microvalves are used for application in the female and the male. After the manufacturing of the first prototype, the valve will be tested in sheep or pigs.

The microvalve which can be employed for fertility control or vasectomies is shown in Figure 5. It consists of two different kinds of polymeric layers: a structural and a sacrificial layer, which are fabricated by the μSL. The main element of the valve is the multifunctional polymer actuator, which serves at the same time as a closure element of the microvalve. The wireless communication principle via an ID-tag is used as previously described. The ID-tag is deposited on the surface of the polymer actuator. The corresponding reader/transmission station is outside the human body. The valve is closed in the initial state if no RF signal is sent to the ID-tag. In this state, the infertility is set. If sperm or ovum should pass through the microvalve, RF pulses are transmitted by the base station, which is located outside the body, to the valve. Because of the deformation of the actuator material, the microvalve is opened and the female or male is fertile until the valve is closed.

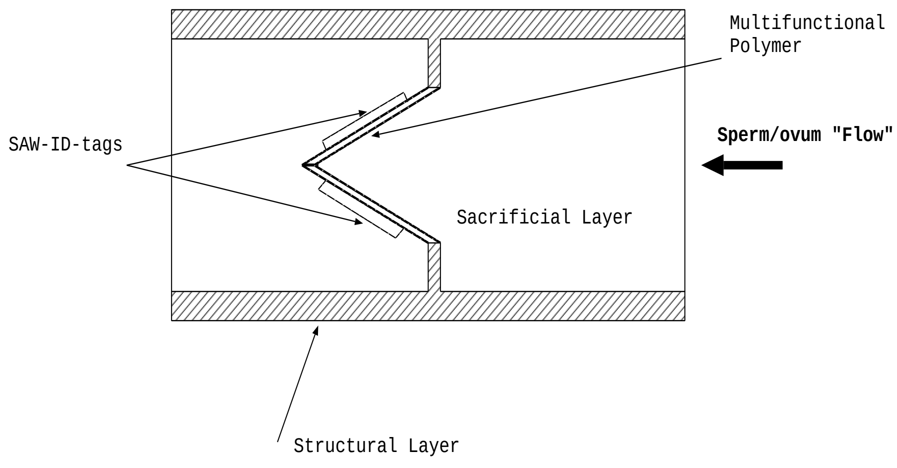

Figure 5. RF controlled microvalve for fertility control in the initial state.

The employment of a RF controlled microvalve could be a step in the direction of reduction of surgical strain on the human and the patient's choice to be fertile or not. Furthermore, it is possible to combine the described actuator principle with a strain sensor, which measures the displacement of the material.[8] Thus, the resulting orifice change could be read by the reader/transmitter outside the body. In addition, the location of the valve in the human body can be determined by the employment of an ID-tag.

4.2. Artificial Venous Valve

Artificial RF controlled venous valves find an application in the vessel system of the human body. Especially veins in the lower extremities suffer from varicose veins.

In a normal venous system the blood pressure in venules and medium veins is actually so low that it cannot oppose the force of gravity without assistance. Valves in these veins act like the valves in the heart, preventing the backflow of blood. As long as the valves function normally, any movement that distorts or compresses a vein will push blood toward the heart .[13] In the case of varicose veins the vessels of the legs and ankles are abnormally swollen or enlarged because of a weaking in the vein's wall. This often leads to pain and swelling in the leg.[15] Varicose veins are caused by damaged and diseased venous valves which permit reversed flow of blood through the valve.

The novel concept of a RF controlled microvalve could help to treat varicose veins. For that purpose the microvalve (Figure 6) is inserted into the varicose vein. The diameter of veins in the leg ranges from 2 to 9 mm.[13] Thus the microvalve should have a diameter in that range.

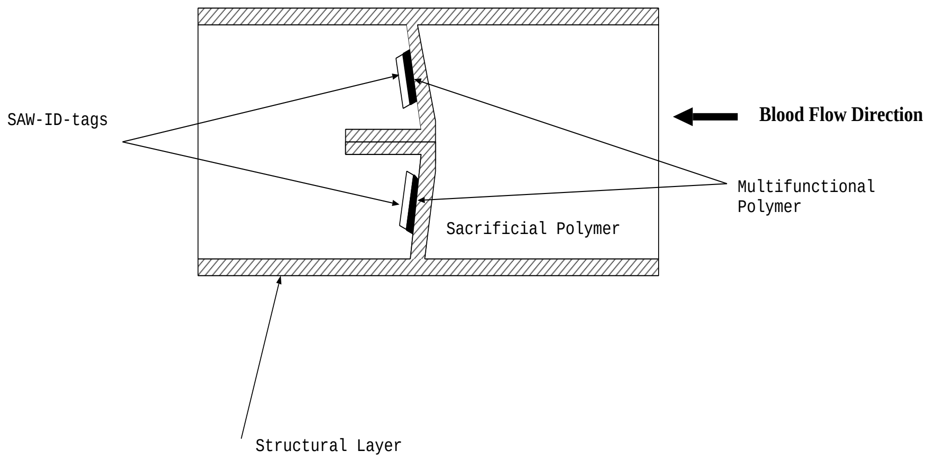

Figure 6. Cross sectional view of a closed RF controlled artificial venous valve.

This RF controlled microvalve follows the fabrication principle with a sacrificial polymer and structural polymer. For the implantation of the valve into the vein, it is desirable to use the passive, wireless and remote communication concept presented above. The ID-tags are printed on the multifunctional piezoelectric actuator.[5] In the initial state the valve is open if no RF signal is applied to the ID-tag. The transmitted RF bursts from the reader/transmitter station outside body will cause deformations in the material employed to close the valve. The microvalve should be constructed in such way that no backflow of blood occurs.

4.3. Flow Cytometry

The basis of flow cytometry analysis is that specific optical characteristics (e.g. light scatter, fluorescence) can provide a measure of the specific physical or chemical properties of biological particles (e.g. size and DNA content).[16] The principle of flow cytometry was integrated into a micromachined silica flow chamber.[16] In this instrument, a collection of small particles is pumped through a specially designed transparent tube. A measurement is made when the particles pass the "sensoring region". This region is delimited by the illumination and collection regions which are provided by light source and optical detector assemblies.

A RF controlled microvalve which uses the wireless communication and actuation principle presented above, could be employed in combination with a flow cytometry instrument as a useful microflow device. The valve could serve as a control element for a stream of particles, which would keep the biological cells of interest in a separate particle chamber for later investigations. The valve also prevents a reverse flow of the cells out of this chamber to the fluid source of the flow cytometry system.

4.4. Drug Delivery

Nowadays the research in drug delivery looks for systems which are capable of delivering precise quantities of a drug at the right time and as close to the treatment site as possible.[17] To achieve these requirements, the micro system technology is used for the fabrication of microflow devices. Micropumps are microflow devices, which can be implanted in the human body. Implantable drug delivery pumps are preferable to therapies that require many injections daily or weekly. Apart from the reduction of injections, drug delivery systems can be implanted at the place where the drug is needed (chemotherapy). This reduces the strain placed on the body by the use of drugs, because the drug is applied at the location where it is to be used.

The control function of the implantable pump is achieved by the employment of wireless communication via RF pulses. In this case, a RF controlled microvalve as previously discussed can be integrated in an implantable drug delivery system. Thus, the pump can be steered by a reader/transmitter station, which is located outside the body. It is possible to set the correct drug dosage (generally in order of μl/min), to be applied at the right time.

4.5. DNA Mapping

The human DNA molecule contains 3 billion bits of information. Present mapping techniques employ electrophoresis and it has taken nearly 20 years to map the whole human genome. One idea to speed up this process is to pull a strand of DNA through a tiny hole in a polymer material. This is done inside a solution of potassium ions and the ion current through the hole is measured. The detected current varies depending on whether the A, G, C or T part of the DNA code is by the hole – in this way the whole sequence can be mapped in possibly a few days (rather than years). However, there are a number of problems with this technique – one key problem is that of poor signal-to-noise ratio (SNR) in the measured current. However, the proposed SAW-on-polymer device provides a means to adaptively modulate the diameter of the hole to optimize the SNR. Alternatively we can adopt a scheme where the hole size oscillates, thus modulating the current to allow lock-in amplifier detection techniques. The use of a lock-in method could significantly improve the performance.

5. OPEN QUESTIONS AND FUTURE WORK

In the last section, we considered five application fields of a RF controlled microvalve. In new fields of research, there are many questions to be answered before any inventions can be safely applied. Above all, in the field of fertility control it is important to make sure that the microvalve works correctly and efficiently to prevent problems which could endanger the patient.

Since the diameter of the sperm and the ovum differ in the order of 5000, an actuator material for the RF controlled microvalve is needed which is capable of expanding in that range of strain. Analysis should also be done to establish whether it is possible to fabricate a valve with a "rest size" of the orifice. Thus, no sperm can pass through the valve. Using μSL, a microvalve with a "rest size" is easier to fabricate than one with no rest valve orifice space.

There is also room for investigation into the expansion of the actuator material, and whether the particular shape of the microvalve has an influence on the displacement of the actuator material. It is not yet known, whether there exists differences in the displacement of different shapes of the valve. The aim is to find out an "optimum" shape which satisfies the requirements of displacement for application in the area of fertility control. Furthermore, it should be established which shape is the easiest to implant in the human body in order to prevent complications in surgery and additional pain for the patient. Initially, these tests, together with tests for the functionality of the valve should be undertaken in animals such as sheep or pigs.

When considering the displacement of the microvalve, it is important to know which frequency causes the biggest material strain. The frequency behavior of the material could be calculated by a simulation of the valve. Together with a simulation of the different shapes of microvalve, this could lead to the discovery of an "optimal" microvalve set up for fertility control. Furthermore, it would also be useful to simulate the pressure and flow behavior of the microvalve. This would establish the actual pressure and flow distributions in the valve. As a result of these simulations, a first model could be constructed following the required design specifications. In the case of the artificial venous valve it is essential to clarify the surgical implantation method. On one hand, it is important that the surgery causes as little pain as possible. On the other hand, the valve should have a stable position in the vein to prevent possible movements of the microvalve within the blood flow system. Moreover, the "life-time" of the valve should be considered in the design process. This is achieved by PC simulation of the microvalve under so called "virtual conditions" and practical material tests in the laboratory.

With respect to the flow cytometry and drug delivery case, the method of implantation and reliability simulation should also be considered. In the DNA mapping case, it is essential to investigate the influence of the hole modulation on the SNR. This will be achieved by piezo-material displacement PC simulations.

6. CONCLUSIONS

In this paper, the employment of a RF controllable microvalve for medical applications was discussed. By using the wireless communication concept via an ID-tag, a valve can be implanted in the human body. This ID-tag is employed to create a passive, wireless and remote communication link between the microvalve and the reader/transmission station. Thus, no extra power supply is required at the application location to drive the valve. The energy which is demanded for the actuation process is provided by RF pulses. These pulses are transmitted by a reader/transmitter station outside of the human body. RF bursts are received by an antenna of the valve and converted into Surface Acoustic Waves (SAWs). These waves propagate along the surface of the piezoelectric actuator and cause the required deflection of the actuator material which is used to drive the valve.

The application which the microvalve is suited to, is determined by the performance of the driving actuator. The structure of the valve depends on some physical parameters. (e.g. voltage, material, volume). The choice of material plays a important role in the function of implantable microvalves. The material has to be compatible with the human body. The microvalve which is considered in this paper consists of a multifunctional polymer developed at the Penn State University, USA. The μSL is employed to fabricate the microvalve with high aspect ratio.

The main application presented in this paper is a RF controlled microvalve employed in the field of fertility control. In comparison to a conventional vasectomy, the application of a microvalve makes it possible to restore fertility by opening the valve. The restoration of fertility in the conventional way is an invasive procedure which causes pain and has a high failure rate.

Artificial venous valves are able to support the blood flow through the veins in order to prevent varicose veins. Thus, they prevent surgical strain on the patient. The motivation implantation of a microvalve in a flow cytometry device is to separate biological particles into special chambers for later investigations. Furthermore, a backflow of this particle into the fluid source is prevented by this microvalve like in the artificial venous valves case. The microvalve also finds application in drug delivery systems. Here, the valve serves as a control element for the drug flow into the body. The valve also could be used as a DNA mapping device. For that purpose the DNA strands are pulled through the microvalve and cause current variations which depend on the different nucleic acid components of the DNA molecule. The application of implantable micro devices requires research effort. The section "open questions and future work" partly discussed the relevant problems, the solution of which will determine the direction of future work in this sector of research.

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