# Low magnetic moment PIN diodes for high field MRI surface coils

Pavel Voskoboynik, Ronald D. Joos, and W. E. Doherty, Jr.
*Microsemi Corporation, Lowell, Massachusetts 01851*

Ron B. Goldfarb
*National Institute of Standards and Technology, Boulder, Colorado 80305*

(Received 19 June 2006; accepted for publication 21 September 2006; published 8 November 2006)

Positive-intrinsic-negative (PIN) silicon diodes are commonly used in magnetic resonance imaging (MRI) coils to perform active or passive blocking and detuning, or to disable circuit functions. However, diode packages with large magnetic moments are known to cause image artifacts in high field MRI systems. In this study, diode packages with low magnetic moment were designed by compensating components of ferromagnetic nickel and paramagnetic tungsten with diamagnetic silver. The new diodes have an initial positive susceptibility up to fields of 1 T and a negative susceptibility from 1 to 7 T. Their magnetic moments are one to two orders of magnitude smaller than those of standard diodes; moments as small as 20 nJ/T at 7 T were achieved. © *2006 American Association of Physicists in Medicine*. [DOI: 10.1118/1.2372216]

Key words: diode packaging, image artifacts, magnetic moment, magnetic resonance imaging, magnetic susceptibility, positive-intrinsic-negative diodes

## INTRODUCTION

High power, thick base layer, silicon positive-intrinsic-negative (PIN) diodes have a large intrinsic region between the *p*- and *n*-type layers. When forward biased with direct current (dc), the diode conducts large radio-frequency (rf) and microwave currents without rectification because of the long carrier lifetimes in the intrinsic region. The effective resistance of a PIN diode increases as dc bias current decreases.

In switch and attenuator applications, the PIN diode should ideally control the rf signal level without introducing distortion that might change the shape of the rf signal. An important additional feature of the PIN diode is its ability to control large rf signals while using much smaller levels of dc excitation.[1] For a typical PIN diode in a power transmit coil, a forward bias dc current of 0.5 A at 1 V can control 25 kW of rf power. For a typical PIN diode in a receive coil, a forward bias dc current of 0.1 A at 1 V can control 1 kW of rf power.

PIN diodes are used in commercial magnetic resonance imaging (MRI) scanners as rf switching elements. Here, the diodes are located in transmit and receive coils to perform active or passive blocking and detuning, or to disable circuit functions.[2]

One problem with standard PIN diodes is that magnetic materials used in diode packaging create image artifacts in high field MRI systems above 1.5 T. Here we report on the design, fabrication, and testing of a new PIN diode package in which the magnetic moment is minimized at high magnetic fields. The small net moment is obtained by balancing the large but saturating ferromagnetic moment of nickel, the paramagnetic moment of tungsten, and the diamagnetic moment of silver.

## DIODE PACKAGE DESIGN

Packaging provides a reliable and rugged enclosure for the passivated diode silicon chip. A metallurgical bond between the silicon chip and the contact pins of the package is needed. The pin-die-pin subassembly is then enclosed in a glass envelope. The various parts of the package must be thermally matched for expansion to prevent failure over temperature extremes. These requirements limit the selection of package materials, leads, and other attachments. All of these conditions must be satisfied before the magnetic moment of the package can be adjusted.[3,4]

Tungsten pins are required to match the thermal expansion coefficient of the silicon chip. Typical construction requires nickel plating of the tungsten pins for adhesion, followed by a plating layer(s) to allow bonding to the silicon. Nickel is ferromagnetic and tungsten is paramagnetic (have positive susceptibility). The silicon and the sealing glass are diamagnetic (have negative susceptibility).

Table I shows values of susceptibility of typical construction materials. Volume susceptibility is defined as $\chi = M/H$, where $M$ is the magnetization and $H$ is the magnetic field strength, both in SI units of A/m; $\chi$ is dimensionless. $M$ is calculated as magnetic moment $(\mathrm{A}\cdot\mathrm{m}^2)$ divided by specimen volume $(\mathrm{m}^3)$. For paramagnetic and diamagnetic materials, $\chi$ is the slope of the plot of $M$ vs $H$. The magnetic flux density in free space $B$, in units of T, is equal to $\mu_0 H$, where $\mu_0 = 4\pi \times 10^{-7}$ H/m.

A proprietary commercial technique was used to apply a thin layer (less than 1 $\mu$m) of nickel on the tungsten pins. This was followed by a thin layer of gold and then silver. The resultant seal assembly, even with the small amount of nickel, had relatively low magnetic moment and susceptibility. While these magnetic properties would be acceptable for low field MRI, they are still too large for high field MRI above 3 T.

TABLE I. Volume susceptibility $\chi$ of materials used in PIN diodes (Ref. 4).[a]

| Material | $\chi$ ($10^{-6}$ SI units) | Material | $\chi$ ($10^{-6}$ SI units) |
|---|---|---|---|
| Gold | −34 | Silicon | −4.2 |
| Glass (average) | −33 | Air (NTP) | +0.36 |
| Silver | −24 | Tungsten | +77 |
| Lead | −15.8 | Molybdenum | +123 |
| Copper | −9.63 | Rhodium | +169 |
| Water | −9.05 | Nickel | ferromagnetic |

[a]Divide by $4\pi$ to get volume susceptibility in CGS units.

Various PIN diodes in several different package styles were then evaluated to design a PIN diode with low magnetic moment at high field. The magnetic moments of some diodes were too large to be tuned out with end caps of reasonable size. The larger "090" pin devices (pins 2.3 mm in diameter), similar to the UM4001/UMX5601SM, would require a reduction in the pin length to reduce the magnetic moment. The smaller "045" pin devices (pins 1.1 mm in diameter) were constructed with standard pin lengths to be compatible with the UM9601. Here, solid silver end caps were used to balance the magnetic moment. It was also decided to indicate the polarity of the diode by utilizing a round end cap to mark the anode; the cathode is square. This design was also able to make the devices compliant with European restrictions on hazardous substances (RoHS).[5]

The magnetic moments of four diodes with silver end caps of different thicknesses were measured and a linear regression analysis was used to determine the thickness of the end caps required to set the magnetic moment to approximately zero. This was done for both the 090 and 045 pin devices.

## MAGNETIC MEASUREMENTS

Magnetic moments were measured at ambient temperature (298 K) in fields up to 5.6 MA/m (7 T) with a magnetometer based on a superconducting quantum interference device (SQUID). PIN diodes with very small moments were measured in groups of two or more to increase the ratio of signal to noise.

Standard diodes were overall paramagnetic with large susceptibilities, occasionally with a low-field step due to their ferromagnetic components. Optimized low-moment diodes had small ferromagnetic moments (from nickel) of the same order of magnitude as their diamagnetic moments (mostly from silver). The ferromagnetic component saturated at fields of about 1 T, whereas the diamagnetic component was proportional to field up to 7 T. Composite magnetization curves therefore exhibited an initial increase at low fields, followed by a roll-over and then a linear decrease at high fields. A small amount of hysteresis was apparent. Magnetic moments of low-moment diodes were less than 10% of that of standard diodes at fields below 1 T and were less than 1% at 7 T.

Figures 1–3 show the magnetization curves of standard PIN diodes UM4001B, UM9601, and UM9995. (UM9995 is similar to a standard diode, UM9601, except that it has tin instead of gold/nickel on its leads.) Average susceptibilities may be computed from the slopes of the fitting lines.

Figures 4 and 5 show the magnetization curves of optimized PIN diodes UMX5601SM and UMX5104SM.

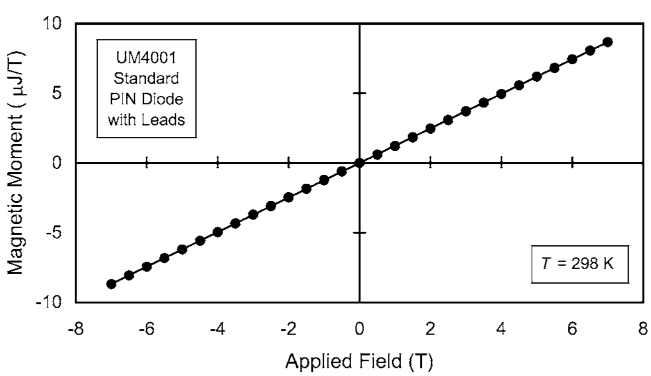


FIG. 1. Magnetic moment of standard diode UM4001B (with leads) as a function of field. Diode mass (including leads) is 0.337 g, with an approximate volume of 0.038 $cm^3$. Mass susceptibility is $4.62\times10^{-9}$ $m^3$/kg SI ($3.68\times10^{-7}$ emu/g CGS). Volume susceptibility is $4.2\times10^{-5}$ dimensionless SI ($3.3\times10^{-6}$ emu/$cm^3$ CGS).

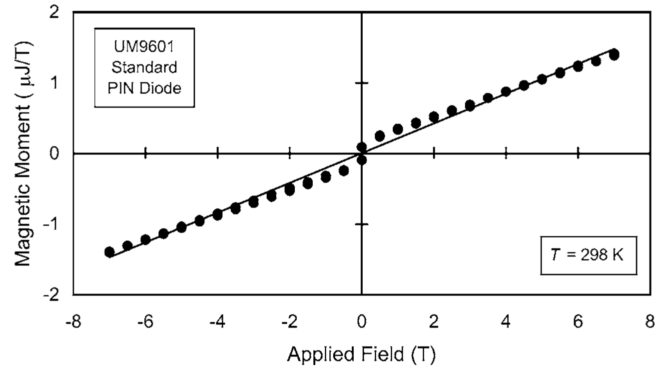


FIG. 2. Magnetic moment of standard diode UM9601 as a function of field. Diode mass is 0.135 g, with an approximate volume of 0.015 $cm^3$. Mass susceptibility is $1.97\times10^{-9}$ $m^3$/kg SI ($1.58\times10^{-7}$ emu/g CGS). Volume susceptibility is $1.8\times10^{-5}$ dimensionless SI ($1.4\times10^{-6}$ emu/$cm^3$ CGS).

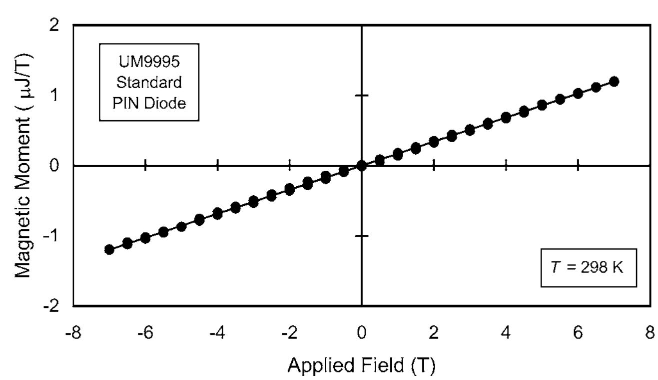


FIG. 3. Magnetic moment of standard diode UM9995 as a function of field. Diode mass is 0.139 g, with an approximate volume of 0.015 $cm^3$. Mass susceptibility is $1.55\times10^{-9}$ $m^3$/kg SI ($1.23\times10^{-7}$ emu/g CGS). Volume susceptibility is $1.4\times10^{-5}$ dimensionless SI ($1.1\times10^{-6}$ emu/$cm^3$ CGS).

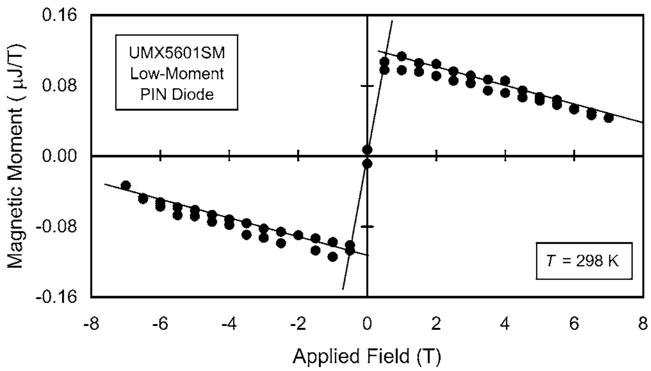


FIG. 4. Magnetic moment of low-moment diode UMX5601SM as a function of field. Diode mass is 0.398 g, with an approximate volume of 0.044 $cm^3$. Low field: mass susceptibility is $6.51\times10^{-10}$ $m^3/kg$ SI ($5.18\times10^{-8}$ emu/g CGS); volume susceptibility is $5.9\times10^{-6}$ dimensionless SI ($4.7\times10^{-7}$ $emu/cm^3$ CGS). High field: mass susceptibility is $-3.33\times10^{-11}$ $m^3/kg$ SI ($-2.65\times10^{-9}$ emu/g CGS); volume susceptibility is $-3.0\times10^{-7}$ dimensionless SI ($-2.4\times10^{-8}$ $emu/cm^3$ CGS). The maximum specific magnetization in a field of 1 T was $2.8\times10^{-4}$ $A\cdot m^2/kg$ SI ($2.8\times10^{-4}$ emu/g CGS), corresponding to a volume magnetization of about 2.6 A/m SI ($2.6\times10^{-3}$ $emu/cm^3$ CGS=$3.2\times10^{-2}$ G CGS).

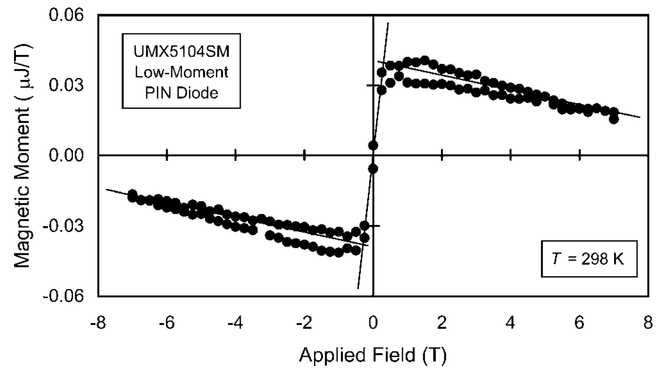


FIG. 5. Magnetic moment of low-moment diode UMX5104SM as a function of field. Diode mass is 0.154 g, with an approximate volume of 0.017 $cm^3$. Low field: mass susceptibility is $1.15\times10^{-9}$ $m^3/kg$ SI ($9.17\times10^{-8}$ emu/g CGS); volume susceptibility is $1.0\times10^{-5}$ dimensionless SI ($8.3\times10^{-7}$ $emu/cm^3$ CGS). High field: mass susceptibility is $-2.72\times10^{-11}$ $m^3/kg$ SI ($-2.16\times10^{-9}$ emu/g CGS); volume susceptibility is $-2.4\times10^{-7}$ dimensionless SI ($-1.9\times10^{-8}$ $emu/cm^3$ CGS). The maximum specific magnetization in a field of 1 T was $2.6\times10^{-4}$ $A\cdot m^2/kg$ SI ($2.6\times10^{-4}$ emu/g CGS), corresponding to a volume magnetization of about 2.3 A/m SI ($2.3\times10^{-3}$ $emu/cm^3$ CGS=$2.9\times10^{-2}$ G CGS).

(UMX5104SM is operationally similar to standard diode UM7104SM.) Average susceptibilities in the low and high field regions may be computed from the slopes of the fitting lines.

## CONCLUSION

Magnetic measurements of several PIN diodes commonly used in MRI showed magnetic moments that were unacceptably large for some applications. A design study was undertaken to determine how to fabricate diode packages with low magnetic moment. The procedure was to reduce the ferromagnetic nickel content to a minimum, reduce the relatively large quantity of parametric tungsten, and then tune the resultant package with diamagnetic silver end caps. At any field, the net magnetic moment is the sum of the individual moments of the nickel, tungsten, and silver. Overall pin lengths were reduced in the larger 090 pin size devices to allow the use of silver end caps of reasonable thickness. The smaller 045 pin size devices were unchanged in length since modest silver end caps were sufficient. In the range from 0 to 1 T the devices are effectively paramagnetic due to the saturating nickel component, whereas in the range from 1 to 7 T the devices are effectively diamagnetic, with a small amount of magnetic hysteresis.

## ACKNOWLEDGMENTS

We thank Ron Watkins, GE Global Research, Niskayuna, NY, for imaging the low-moment diodes on a GE 1.5 T scanner at several stages of package development. Certain commercial devices are identified only to specify the experimental study adequately. This does not imply endorsement by NIST or that the devices are the best available for the purpose.

[1]W. E. Doherty, Jr. and R. D. Joos, *The PIN Diode Circuit Designers' Handbook*, Version 3 (Microsemi Corporation, Lowell, MA, 2006).
[2]W. A. Edelstein, C. J. Hardy, and O. M. Mueller, "Electronic decoupling of surface-coil receivers for NMR imaging and spectroscopy," J. Magn. Reson. (1969-1992) **67**, 156–161 (1986).
[3]B. Muller-Bierl, H. Graf, G. Steidle, and F. Schick, "Compensation of magnetic field distortions from paramagnetic instruments by added diamagnetic material: Measurements and numerical simulations," Med. Phys. **32**, 76–84 (2005).
[4]J. F. Schenck, "The role of magnetic susceptibility in magnetic resonance imaging: MRI magnetic compatibility of the first and second kinds," Med. Phys. **23**, 815–850 (1996).
[5]Directive 2002/95/EC of the European Parliament and of the Council, 27 January 2003, "On the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment," effective 1 July 2006.